A change of perspective

From adapting working environments towards wearing a passive trunk exoskeleton

Since there are many factors contributing to the onset of low back pain, researchers have for many years tried to understand the underlying mechanisms of this multifaceted disorder. With no clear pathological cause established in almost 90% of the cases (Krismer et al., 2007), treatment is not very successful. Thus, the prevalence of low back pain keeps on rising. Therefore, the million-dollar question is: how can we support people who suffer from low back pain and how can we prevent low back pain in those who are still healthy?

Saskia Baltrusch, Axel Koopman, Han Houdijk and Jaap van Dieën

Did you ever experience low back pain? You are not alone! About 80% of all adults experience low back pain at some point in their life. It is the second most common reason for disability, with over a 100 million lost work days a year, reported in the UK (Croft, 1993). Also, it is tremendously expensive. The Netherlands

Figure 1. Working conditions as a luggage handler.

spends more than 3 billion euros on low back pain each year, with a ratio of 12% to 88% between direct costs, such as medical care, and indirect costs, such as production loss and disability costs (Lambeek et al., 2011).

Physically demanding jobs that require heavy lifting, trunk rotations or working in awkward postures for a longer period of time lead to high back loading and might sooner or later result in low back injury and pain (Coenen et al., 2014a; Coenen et al., 2014b; Griffith et al., 2012, Faber et al., 2009). Therefore, researchers have focused on adapting working environments to reduce mechanical risk factors. For example, increasing lifting height, reducing the lifted load, or introducing lifting robots have shown to be promising in terms of reducing the load on the lower back (Faber et al., 2009; Marras et al., 1999). Nevertheless, these adaptations are often difficult to implement.

Let us illustrate the challenges of reducing physical workload with a practical example of an airline company. An employee working at the luggage handling service has to handle about 300 suitcases per flight for up to 9 flights a day. These suitcases can weigh up to 45 kg. Considering the promising adaptations of the working environment mentioned earlier, there are different challenges to face. Reducing the mass that needs to be lifted may not be feasible in our example. When checking in luggage, there is no strict weight limit. By paying some extra fee, travellers can check in luggage of any weight. The lifting height is another challenge in the working environment of a luggage handler. Their main task consists of lifting suitcases from conveyer belts onto carts or the other way around (figure 1). These conveyer belts used to be built at ankle height, forcing the luggage handlers to bend down even further and increasing the load on their back. Companies therefore started to increase lifting height to reduce back loading by adjusting old conveyer belts from ankle height to hip height. Nevertheless, old conveyor belts are still in use. Another way airline companies try to reduce physical workload and specifically the load on the back, is the implementation of lifting devices. However, luggage handlers perceive the use of lifting devices as too slow and feel interfered with their normal working behaviour. As soon as work must be done fast, they prefer manual handling. So, how can we effectively assist those people when it comes to reducing the load on their lower back? Perhaps we need to change our perspective: what if we do not adapt the working environment, but instead enhance the ability of the worker through wearable, assistive devices?

This challenge was the starting point of the SPEXOR project (www.spexor.eu), a collaboration between institutions from 5 different countries, including the Netherlands represented by the Vrije Universiteit Amsterdam and the Rehabilitation Center Heliomare. The aim of this project is to develop a spinal exoskeleton that assists the user's movements and reduces the load on the lower back. To arrive at a first prototype, VU Amsterdam took the responsibility to define the biomechanical requirements for such a device, whereas Heliomare assessed the design requirements from the potential end-user's point of view. The established requirements and initial benchmark testing of an existing commercial device will be described briefly in the following paragraphs.

Defining design requirements

In daily live, peak compression forces on the low back can easily reach 5000 N (Kingma et al., 2016), for example when lifting a box of 20 kg. This value of 6000 N is within the range in which damage of vertebrae can occur. Therefore, the National Institute for Occupational Safety and Health (NIOSH) developed a guideline to ensure safe lifting in working environments (Waters et al., 1993). The recommended weight limit according to this guideline is widely accepted as a tool for answering the question: 'Is this weight too heavy for this task?'. As mentioned before, in practice it appears difficult working within these limits at all times. The main aim of the SPEXOR project is to reduce peak spinal compression forces during load handling tasks. By supporting the upper body during trunk flexion and lifting, and thereby reducing the required activity of the back muscles, peak compression forces will decrease, leading to a smaller risk of tissue damage and consequently lower risk of getting low back pain. Our ambition is to generate a supporting extension moment during trunk flexion and lifting between 50-100 Nm, resulting in a reduction of peak compression force by 1000-2000 N. Additionally, literature has shown strong evidence that working in a bent posture is a major risk factor for developing low back pain (Hoogendoorn et al., 2000). Therefore, in SPEXOR, a warning signal or a hard stop of the system will be generated whenever subjects are bending beyond a subject specific limit (80% of maximum lumbar flexion) to reduce the risk of developing low back pain.

The end-users' point of view

To understand the complex demands on people suffering from low back pain and to be able to develop a device that truly meets the end-user's demands, communication with these people is essential. Therefore, we conducted focus group studies with low back pain patients, health care professionals and luggage handlers. We discussed the main problems they face due to low back pain and their wishes and doubts about such an exoskeleton. One of the main findings in these focus groups was that patients want such a device to help them function independently and consequently using the device should not require any

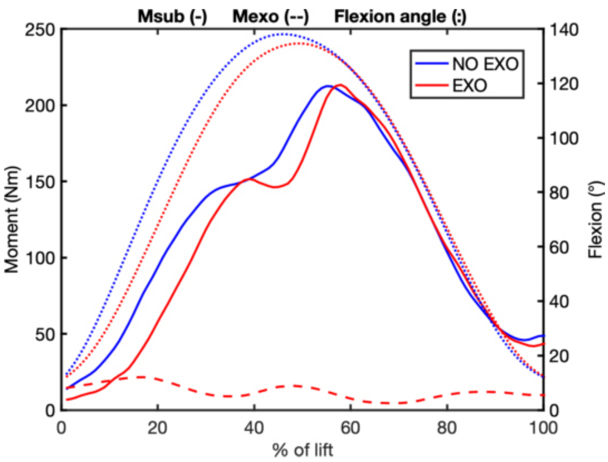

Figure 2. Time series of the moment generated by the subjects (MSUB, solid), the exoskeleton (MEXO, striped), and the flexion angle (dotted), over the whole lifting cycle averaged over subjects.

help for example for donning and doffing or for making adjustments. Another important point was, having a versatile device that can provide different modes of support, depending on the task performed. In certain tasks one might not want to have as much support as in others. Main doubts were the fear of getting dependent on the exoskeleton and getting weaker physically when using it too often.

Benchmarking: Testing the state of the art

Testing an exoskeleton that is already on the market was an important first step to define the requirements for the SPEXOR device, but also to understand the challenges of current designs. How can we improve the current state of the art? The test procedure consisted of three parts: (1) biomechanical testing: how does the device affect the loading on the lower back? (2) physiological testing: does the exoskeleton change the metabolic demand and potential fatigue of the user? And (3) functional testing: does the exoskeleton support or hinder the user in daily activities? For this test procedure we used a passive exoskeleton (Laevo, Intespring, Delft, The Netherlands) that generates a support at the lower back when the user is bending forward by transferring the load from the lower back to the chest and upper legs.

Biomechanical testing

To calculate the loading on the low back we measured movements, forces and muscle activity in participants performing different load handling tasks with and without the exoskeleton (Koopman et al., online). During static bending tasks, the moment generated by the subjects around the low back was reduced by 15-20% when wearing the exoskeleton. The exoskeleton generated around 20 Nm support. However, the back-muscle activity when wearing the exoskeleton was not always significantly lower compared to not wearing it. This could be explained by the large lumbar flexion angle that occurred in some participants. These participants showed the so-called flexion-relaxation phenomenon, in which the extension moment around the lower back is not generated by active muscle force but by passive tissues in the low back. Thus in these postures, the flexion moment due to gravity is balanced by an extension moment produced by passive tissues and when the exoskeleton then also produces an extension moment the subject would have to counteract this moment, by abdominal activity, to maintain the same posture. This will increase low back loading. These results indicate that flexion-relaxation and its inter-individual variation should be considered in future exoskeleton designs.

During dynamical lifting from ankle height, we found that the exoskeleton did not affect lifting strategy in terms of movement speed or lifting style. The support of the exoskeleton was similar as in the static bending tasks (20 Nm). However, during lifting, the moment that needs to be generated is twice as high (210 Nm) compared to static bending (100 Nm). Therefore, the relative effect of the exoskeleton was only around 10% (figure 2). In addition, we found a substantial reduction in support (of almost 10 Nm) during upward movement compared to downward movement. Due to friction in the system, energy is lost in the device, leading to less support at peak loading, just after picking up the load. Although effects were small, peak moments generated by the participants were significantly reduced while using the exoskeleton. This finding was supported by reduced back muscle activity by around 10%. These results indicate that while a reduction in low back load can be reached with an exoskeleton, we have to aim at more support and less hysteresis of future exoskeletons, to achieve more substantial reductions in loading on the lower back during dynamical lifting tasks.

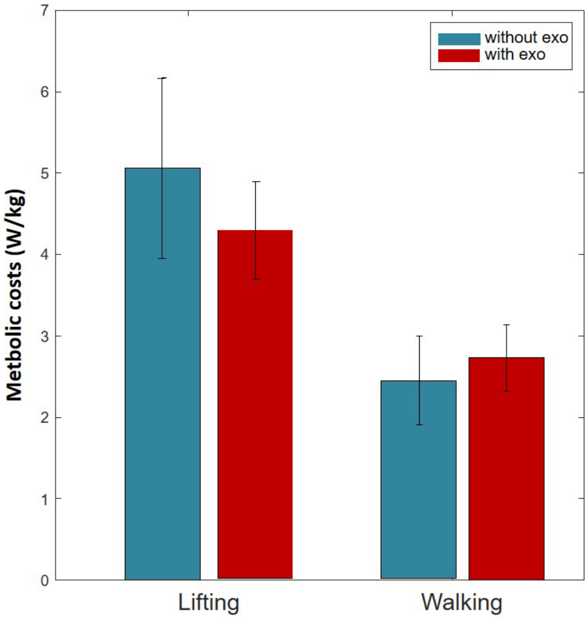

Figure 3. Metabolic costs during lifting and walking with and without the exoskeleton.

Physiological testing

According to the guidelines of the National Institute for Occupational Safety and Health (NIOSH), besides the mechanical load, physiological strain needs to be taken into account, to guarantee safe manual material handling. High physiological strain can result in systemic or local fatigue (Waters et al., 1993), leading to an increased risk of lifting-related low back pain. For physiological testing, we measured the aerobic strain of the participants, by assessing the oxygen consumption during lifting and walking (Baltrusch et al., under review). Participants had to lift and lower a box of 10 kg for 5 min at a frequency of 8 lifts per minute. In addition, we assessed the aerobic load while walking on a treadmill, to test the potential hindrance of the device during this task. We found that oxygen consumption decreased when wearing the device during lifting (figure 3). This indicates that this passive exoskeleton supports the user during lifting, probably by reducing muscular effort in the low back, which might reduce fatigue during working tasks, but also observed changes in lifting technique, from squat to stoop lifting, may have contributed to this effect. On the other hand, during walking the oxygen consumption increased (figure 3), which indicates that the device could hinder the user in other functional tasks that occur at a worksite that might offset the positive effect on fatigue.

Functional testing

To further assess the effect of the passive exoskeleton on functional performance, we developed a test battery of 12 different tasks that can be found in many work environments (Baltrusch et al., 2018). This test battery consists of range of motion tasks, such as forward bending, rotation or squatting, and tasks that are performed commonly in work settings, such as carrying, lifting, walking and stair climbing. Our aim was to test both tasks that are expected to be supported as well as tasks that might be hindered. Performance of all tasks was measured in terms of objective performance, i.e. time to perform the task, and in terms of subjective performance, i.e. perceived task difficulty. The results showed that the passive exoskeleton only increased performance in static forward bending, but decreased performance in several other tasks (figure 4). Especially tasks that required hip flexion were hindered by the device. The subjective estimation of perceived task difficulty showed a similar picture, with only one task being perceived as easier when wearing the exoskeleton and a number of other tasks being perceived as more difficult. These findings indicate the importance of the possibility to disengage the hip spring in the device when the type of task that is performed requires unrestricted hip movement.

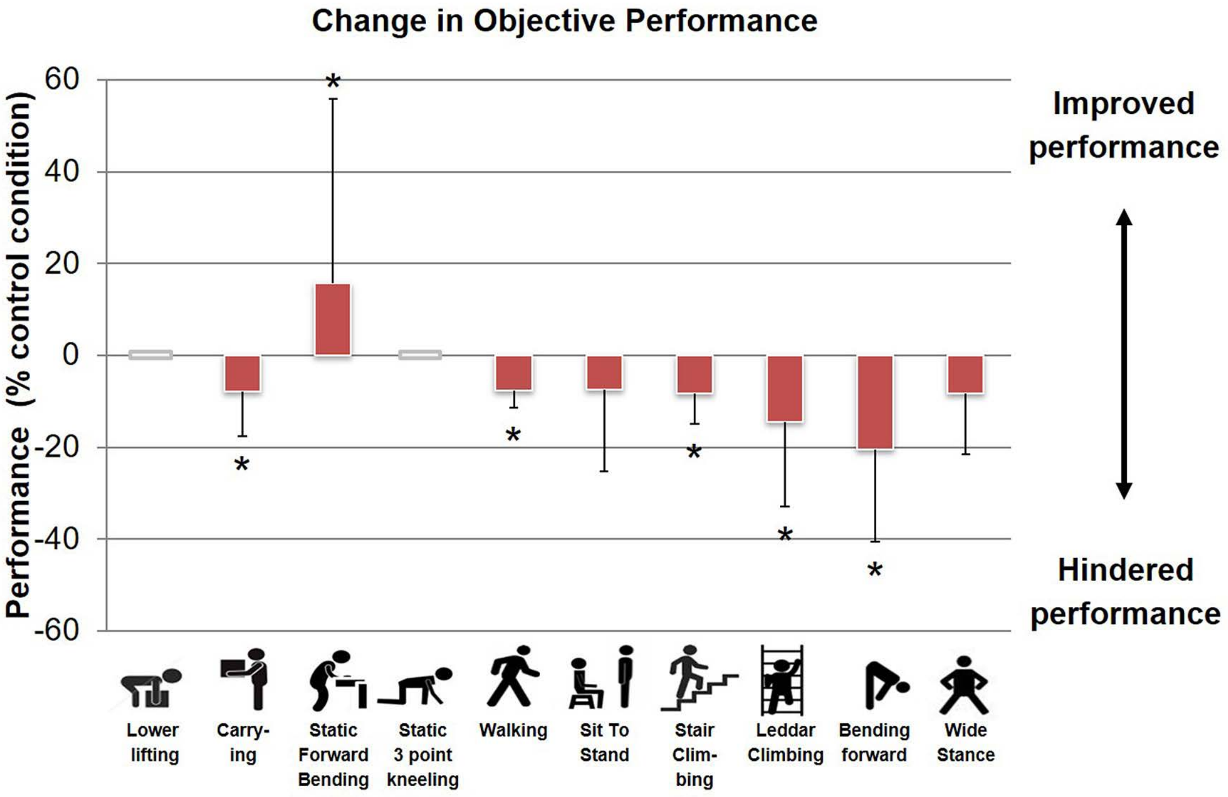

Figure 4. Change in objective performance when wearing the exoskeleton, compared to not wearing the exoskeleton. Note that only one task (static forward bending) increased in performance, whereas several other tasks decreased in performance when wearing the exoskeleton.

Design improvements and further developments

Based on the results from biomechanical, physiological and functional testing, we could define three important design improvements with respect to the benchmark Laevo exoskeleton, to be considered when developing the Spexor device. First, prevention of the flexion-relaxation phenomenon or prevention of providing support when this phenomenon occurs is needed. To do so, the exoskeleton design could prevent deep flexion angles in the low back, but make the person use hip flexion when bending forward. Second, the data showed that a new design should provide more support with less hysteresis. Finally, disengaging the device whenever the support is not needed becomes essential when aiming for higher versatility and freedom of movement.

Going back to the example of the luggage handler, an exoskeleton will only be used during a working day if the exoskeleton provides sufficient support and when this support can be switched on when needed and switched off when a task does not require support. Based on these design requirements, we have developed a first SPEXOR protoype that is being tested with employees from load handling professions. First results showed that we are making progress to provide the end-user of our Spexor exoskeleton with more support, less hysteresis, improved versatility and unrestricted hip flexion (Näf et al., 2018). This prototype will be expanded with active components that should further increase support of the lower back and enhance control of this support in various work related tasks. Follow our progress at the project website.[1]

References

Baltrusch, S.J., van Dieën, J.H., van Bennekom, C.A.M., Houdijk, H., (2018). The effect of a passive trunk exoskeleton on functional performance in healthy individuals. *Applied ergonomics 72*, 94-106.

Baltrusch, S.J., van Dieën, J.H., Bruijn, S.M., Koopman, A.S., van Bennekom, C.A.M., Houdijk, H. The effect of a passive trunk exoskeleton on metabolics costs during lifting and walking. *Ergonomics*. (conditionally accepted 2018)

Coenen, P., Kingma, I., Boot, C.R., Bongers, P.M., van Dieen, J.H. (2014a). Cumulative mechanical low-back load at work is a determinant of low-back pain. *Occupational and Environmental Medicine 71*, 332-337.

Coenen, P., Gouttebarge, V., van der Burght, A.S.A.M., van Dieen, J.H., Frings-Dresen, M.H.W., van der Beek, A.J., Burdorf, A. (2014b). The effect of lifting during work on low-back pain – a health impact assessment based on a meta-analysis. *Occupational and Environmental Medicine, 71*, 871-877.

Croft, P., Rigby, A.S., Boswell, R., Schollum, J., Silman, A. (1993). The prevalence and characteristics of chronic widespread pain in the general population. *Journal of Rheumatology, 20*(4),710-3.

Faber, G. S., Kingma, I., Kuijer, P. P., van der Molen, H. F., Hoozemans, M. J., Frings-Dresen, M. H., van Dieën, J. H. (2009). Working height, block mass and one- vs. two-handed block handling: the contribution to low back and shoulder loading during masonry work. *Ergonomics, 52*, 1104-1118.

Griffith, L.E., Shannon, H.S., Wells, R.P., Walter, S.D., Cole, D.C., Cote, P., Frank, J., Hogg-Johnson, S., Langlois, L.E. (2012). Individual participant data meta-analysis of mechanical workplace risk factors and low back pain. *American Journal of Public Health, 102*, 309-318.

Hoogendoorn, W. E., Bongers, P. M., de Vet, H. C., Douwes, M., Koes, B. W., Miedema, M. C., Bouter, L. M. (2000). Flexion and rotation of the trunk and lifting at work are risk factors for low back pain: results of a prospective cohort study. *Spine, 25*(23), 3087–92.

Kingma, I., Faber, G.S., van Dieën, J.H. (2016). Supporting the upper body with the hand on the thigh reduces back loading during lifting. *Journal of Bioemchanics, 49*(6), 881-889.

Koopman A.S., Kingma I., Faber, G.S., de Looze, M.P., van Dieën, J.H., Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks. *Journal of Biomechanics* (online).

Krismer, M., van Tulder, M. (2007). Low back pain (non-specific). *Best Practice and Research Clinical Rheumatology, 21*(1), 77-91.

Lambeek, L.C., van Tulder, M.W., Swinkels, I.C.S., Koppes, L.L.J., Anema, J.R., Mechelen, W. (2011). The trend in total cost of back pain in The Netherlands in the period 2002 to 2007. *Spine, 36*(13), 1050-1058.

Marras, W. S., Granata, K. P., Davis, K. G., & Allread, W. G. (1999). Effects of box features on spine loading during warehouse order selecting. *Ergonomics, 42*(7), 980-996.

Näf, M. B., Koopman, A. S., Baltrusch, S., Rodriguez-Guerrero, C., Vanderborght, B., Lefeber, D. (2018). Passive Back Support Exoskeleton Improves Range of Motion Using Flexible Beams. *Frontiers in Robotics and AI, 5*(72).

Waters, T.R., et al. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

About the author:

MSc S. Baltrusch
PhD Student
Research and Development, Heliomare
The Netherlands
s.baltrusch@heliomare.nl

MSc A. Koopman
PhD Student
Faculty of Behavioural and Movement Sciences
Vrije Universiteit Amsterdam
The Netherlands

dr. H. Houdijk
Associate Professor
Faculty of Behavioural and Movement Sciences
Vrije Universiteit Amsterdam
The Netherlands

Prof. dr. J. van Dieën
Professor of Biomechanics
Faculty of Behavioural and Movement Sciences
Vrije Universiteit Amsterdam
The Netherlands

---

[1] www.spexor.eu.