FYSIEK

A passive lower-limb industrial exoskeleton

Subjective evaluation during and after simulated assembly

In recent years, exoskeletons have been seen as an opportunity to prevent work-related musculoskeletal complaints or to have employees with musculoskeletal complaints reintegrate sooner, faster or more easily. In this manuscript, we propose a passive lower-limb exoskeleton, which is interesting for employees who perform mainly standing work and where the use of a chair is not possible in terms of space and safety.

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Introduction

The use of exoskeletons in an occupational setting aims supporting workers in heavy load lifting or repetitive motions (de Looze et al., 2015). This also means that an indirect aim of using exoskeletons is to reduce the prevalence and incidence of work-related musculoskeletal complaints, since heavy loading and repetition are among its most important contributors (Da Costa & Vieira, 2010; Kausto et al., 2011; Mayer et al., 2012).

When evaluating exoskeletons in the laboratory or in the field, aspects such as biomechanics, energetics, safety, and subjective assessment can be included. Although highly dependent on and variable among individuals, subjective assessments are critical when it comes to acceptance and actual use of an exoskeleton in practice. Subjective assessments can be collected with respect to, e.g., usability, user acceptance, or discomfort. Several recent studies report the subjective assessments of different exoskeletons: Laevo®, Robo-Mate®, EksoVest®, EXHAUSS Stronger®, FORTIS®, and ShoulderX®.

The Robo-Mate® was assessed for its usability, which was rated acceptable (Huysamen et al., 2018). All of the seven exoskeletons mentioned above showed only little discomfort in target body regions or showed decreased discomfort when the exoskeleton was worn compared to when it was not worn (Bosch et al., 2016; Huysamen et al., 2018; Kim et al., 2018a; Kim et al,. 2018b; Theurel et al., 2018; Alabdulkarim & Nussbaum, 2019).

Figure 1. Chairless Chair®. Picture adapted from: https://www.noonee.com/ (© noonee AG).

Objective

The exoskeleton investigated in this study was the Chairless Chair® (noonee AG, Switzerland), which is a passive lower-limb exoskeleton that allows the standing worker to sit for short periods at different seat heights (Figure 1). The aim of this study was to evaluate subjective assessment of the Chairless Chair in different sitting heights (standing vs. high sitting and low sitting).

Note that the study results described in this manuscript are part of a larger study in which the overall goal was to perform a biomechanical-physiological evaluation of

Table 1. Questionnaire items on which participants replied on a 10-point scale, ranging from 1 (completely disagree) to 10 (completely agree).

General items	
1	The exoskeleton sat comfortably
2	The exoskeleton was easy to handle
3	I was able to work precisely with the exoskeleton
4	The exoskeleton is suitable for the simulated assembly task
5	I can imagine working with the exoskeleton over a longer time
Specific items	
1/2	The working posture was pleasant while sitting in the high/low configuration
3/4	I felt very safe while sitting in the high/low configuration
5/6	I would have liked to change my working posture while sitting in the high/low configuration

the Chairless Chair® in simulated assembly. Results of other parts of the study, i.e. muscle activity and posture evaluations, have already been presented at several national and international conferences (Luger et al. 2018a; Luger et al. 2018b; Luger et al. 2018c; Luger et al. under review). In summary, the muscle activity level of the calf muscle (gastrocnemius medialis) was lower in both low and high sitting on the Chairless Chair® compared to standing, and it was lower in low than in high sitting. The muscle activity level of the vastus lateralis was higher in both low and high sitting on the exoskeleton compared to standing, and it was lower in low than in high sitting. The muscle activity level of the trapezius descendens was higher in both low and high sitting compared to standing. The muscle activity level of the erector spinae lumbalis was higher in high sitting compared to low sitting and standing. The position sensors showed that there was less neck flexion but more back flexion in both low and high sitting compared to standing.

Methods

Forty-six healthy males participated, who had a mean age of 24.8 (SD ± 2.9) years old, a mean height of 182.6 (SD ± 5.5) cm, and a mean body mass of 78.1 (SD ± 8.7) kg. The ethical committee of the University Hospital Tübingen approved the protocol (Project Number 184/2017BO2), and all participants provided their written informed consent.

Seven different experimental conditions were compared, which are a combination of working posture and working height, including: (1) standing posture with optimal working height, (2) standing posture with too low working height, (3) high sitting posture with too high working height, (4) high sitting posture with optimal working height, (5) high sitting posture with too low working height, (6) low sitting posture with too high working height, (7) low sitting posture with optimal working height. The optimal working height was determined according to DIN EN ISO 14738:2009-07, where too low and too high were determined as a deviation of ± 10% from the optimal calculated working height.

During each of the seven conditions, participants performed simulated assembling for 21 minutes including screwing, clip fitting, and cable mounting. Before and after each condition, participated rated their discomfort level on an 11-point numeric rating scale ranging from 0 (no discomfort at all) to 10 (highest imaginable discomfort ever experienced). After the seventh condition, wearer comfort was assessed on a 10-point numeric rating scale ranging from 1 (completely disagree) to 10 (completely agree) using five general items and six specific items for high and low sitting configurations (Table 1).

A two-factor (working posture, working height) repeated measures analysis of variance (ANOVA) was performed on the discomfort data, using post hoc Student's T-Tests with Bonferroni-correction. No interaction term was included because we evaluated an incomplete factorial design. A paired T-Test was used on the six specific questionnaire items comparing the two working postures. The general questionnaire items were described with descriptive statistics. The statistical analyses were performed with JMP (JMP® 13.1.0, SAS Inc., Carry, NC, USA), with $\alpha = 0.05$ or $\alpha = 0.0167$ (Bonferroni-corrected post hoc tests).

Results

Ratings of discomfort significantly differed across the three working postures ($p < 0.01$). Standing had an average discomfort value of 0.57 (SD 1.09), which was significantly lower than low sitting with an average of 1.13 (SD 1.49; $p < 0.01$) and high sitting with an average of 1.37 (SD 1.49; $p < 0.01$). The body regions

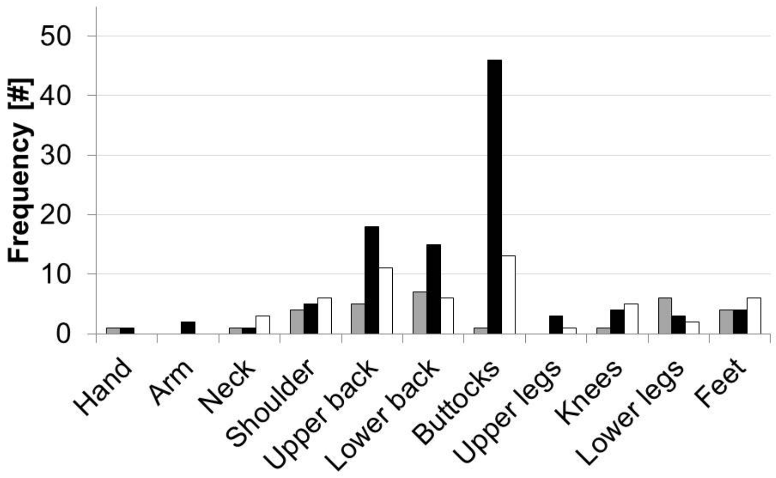

Figure 2. Frequency of reported discomfort per body region (≥ 1), stratified to working posture standing (grey), high sitting (black), and low sitting (white).

with the feedback of 'having the feeling to slide off the sitting pads', which could be a hint for the manufacturer to improve the sitting mechanism and fabric.
A field feasibility study would be highly valuable to give a better view on the user acceptability of the Chairless Chair®. An additional expert and/or user evaluation of workplaces suitable to implement the Chairless Chair® as well as a directive on how long and often employees may use the Chairless Chair® during a work shift without expecting any detrimental effects would be helpful for both researchers and practical ergonomists.

characterized with most discomfort are the buttocks and the back with highest prevalence in the high sitting conditions (Figure 2).

The five general questionnaire items revealed that wearer comfort was rated fair to good (Figure 3), i.e. all items scored on average almost 7 or higher on the 10-point scale. The six specific questionnaire items (Figure 4) showed that low sitting on the Chairless Chair® scored higher for pleasant working posture than high sitting ($p < 0.01$) and scored higher for feeling safe than high sitting ($p < 0.01$). The third questionnaire item about the question whether participants preferred to change their working posture did not significantly differ between low and high sitting on the exoskeleton ($p = 0.0638$).

Conclusion

The positive results of the subjective evaluation, i.e. a low reported level of discomfort of 1.4 on an 11-point numeric rating scale and a fair rating of wearer comfort of 7.9 on a 10-point numeric rating scale, suggest that the Chairless Chair® has the potential to be used in the occupational field. However, it might be worth comparing the evaluated exoskeleton to a regular chair situation, to see whether there are detrimental effects of using the Chairless Chair® instead of a regular chair. We note that the high sitting condition was characterized with most discomfort and lowest wearer comfort, which should be considered in applying the Chairless Chair®, collaborated

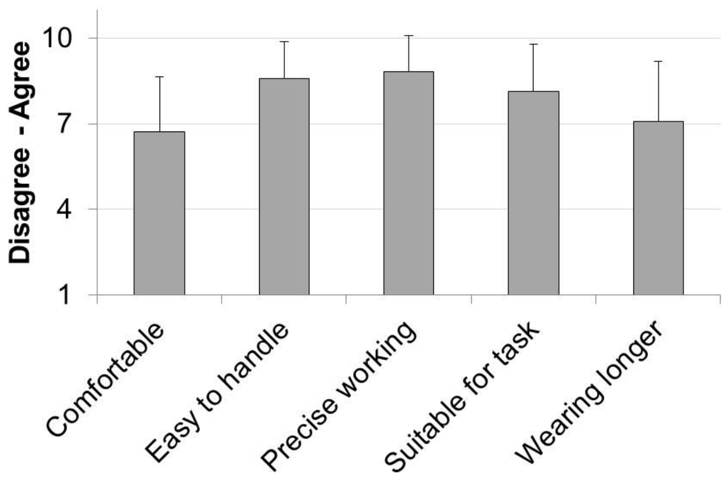

Figure 3. Average response (error bars are SD) to general questionnaire items regarding wearer comfort, rated using a 10-point numeric rating scale (1 = completely disagree; 10 = completely agree). The questionnaire items are listed in Table 1.

Funding

AUDI AG financially supported this study, provided us two Chairless Chairs®, and gave input for the study design. The remaining work of the study was financially supported by an unrestricted grant of the employers' association of the metal and electrical industry Baden-Württemberg (Südwestmetall).

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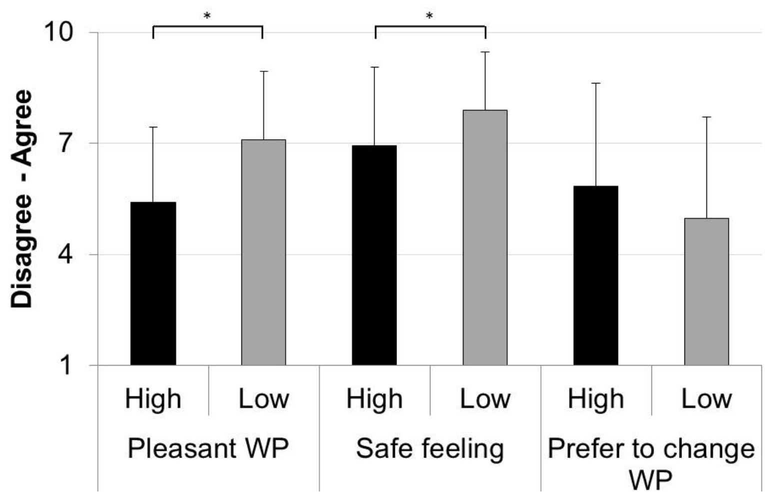

Figure 4. The average response (error bars represent SD) to the specific questionnaire items regarding wearer comfort in low (grey) and high (black) sitting on the exoskeleton, rated using a 10-point numeric rating scale (1 = completely disagree, 10 = completely agree). The questionnaire items are listed in Table 1.

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