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Th. Schmalz, J. Bornmann, B. Schirrmeister, J. Schändlinger, M. Schuler

Principle study about the effect of an industrial exoskeleton on overhead work

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Work-related musculoskeletal disorders are among the most common causes for inability to work in Germany and Europe, and therefore a significant cost factor for companies and healthcare systems. The aim of introducing exoskeletons is to reduce work-related strain on the musculoskeletal system. In this context, the Paexo exoskeleton improves comfort during overhead work. In the principle study presented here, metabolic and electromyographic parameters were recorded during typical overhead work in a laboratory situation in order to objectively assess the effect of the exoskeleton. The results show that using an exoskeleton significantly reduces the user's metabolic energy consumption. The electromyographic analysis demonstrates that strain in the shoulder region, in particular, is considerably reduced with the exoskeleton.

Key words: exoskeleton, upper body exoskeleton, musculoskeletal stress, musculoskeletal diseases

Introduction

Work-related musculoskeletal disorders (WMSDs) are the most common cause for inability to work in Germany and Europe, and therefore a significant cost factor for companies and healthcare systems [1]. According to the Federal Institute for Occupational Safety and Health, the cost of lost production due to musculoskeletal disorders was EUR 17.2 billion in 2016 for Germany alone [2]. Overhead work can cause WMSDs, which are often accompanied by pain. This applies in particular if additional weight in the form of tools must be held [3, 4, 5]. Working with the arms raised over 90° of anteversion for more than 10% of the working hours increases the risk of WMSDs in the shoulder region by one to two thirds. This leads to the conclusion that these postures are directly related to extremely high stresses in the shoulder joint [6]. Ergonomic measures such as the use of handling devices (e.g. hand-held manipulators) have proven beneficial in some areas. However, the low user acceptance due to delays, the increased "movement effort" and the lack of the necessary flexibility when working are major disadvantages [7]. These industrial robots thus cannot adequately replace the required flexibility of human movements in production at this time.

The use of an exoskeleton is an alternative to support overhead work. Exoskeletons are external structures worn on the body that can provide support for a number of tasks and can therefore improve the user's performance. Exoskeletons individually adapted to the person have the potential to reduce the disadvantages described for existing robot systems. They must meet the high demands on functionality, safety and comfort in everyday working life and lead to high acceptance. In this context, the objective proof of a user benefit is very important. This article presents the first studies in which the effect of a passive exoskeleton is measured and tested for a typical overhead task. The focus is on recording metabolic parameters as well as the muscle-related stress in the shoulder joint.

Methods

Exoskeleton tested

Paexo (Fig. 1) is an innovative passive exoskeleton that, at 1.9 kg, is extremely light compared with systems with a similar function [8, 9]. The passive actuators store the energy from the movement and return it when needed. When wearing the exoskeleton, the user experiences perceptible relief of the shoulder joint when working with the arms raised (overhead work) because the weight of the arm is compensated depending on the position of the upper arm. The upper arms are positioned in a channel forearm support that is connected to a joint by a bar. This joint is connected to a movable brace and can move across the back like the scapula. The force is applied to the "hip region" via a belt (backpack principle). The braces on the back can move independently of one another, thus allowing complete freedom of movement of the upper arm and back. The joint is completely freely movable and is located at scapula level. The exoskeleton can be individually adjusted to the user using various adjustment options. The settings for anthropometric parameters and adjusting the level of support are most important. When the exoskeleton has already been adjusted to the user, it can be put on like a backpack in less than 20 seconds. Paexo was developed with users in the automotive industry and tested in series production [10].

Simulation of a typical overhead task under laboratory conditions

To simulate a typical overhead work situation (Fig. 1), a modified shelf was equipped with a height-adjustable task module in a biomechanics laboratory (Fig. 2, left). The adaptations for the overhead tasks to be performed are located on the mod-

Fig. 1 The exoskeleton used in the front and rear view (left) and for work processes in the automotive industry (right)

Fig. 2 Shelf with height-adjustable task module (left) and regulation for height adjustment (hook at eye level, right)

ule. To create equal conditions for all subjects, the eye hooks of the module were positioned at the subject's eye level (Fig. 2, right). The test for the subjects consisted of working with a battery-powered screwdriver (1.5 kg) with the right upper limb above head height for the entire measuring time, with the left upper limb used for supporting tasks (tightening and loosening screws, Fig. 3).

Group of subjects

A group of 12 persons with no known orthopaedic or neurological diseases (24 ± 3 years, 176 ± 15 cm, 73 ± 15 kg, 6 male, 6 female) were recruited as subjects. The subjects had no previous experience in using exoskeletons.

Experimental set-up

After the study design was explained, all subjects were instructed in the correct execution of the task to be performed, including approx. 20 minutes of training with all the measuring equipment applied.

The subjects were divided into two groups for the actual measurements. The first group performed the task twice with the exoskeleton and once without the exoskeleton (A-B-A), the second group twice without and once with the exoskeleton (B-A-B). This was to minimise the impact of adaptation effects on the results. The measurement period for each task was five minutes to ensure that a physiological steady state was reached. There was a 20-minute break between each individual task. Before every task, the resting values of the metabolic parameters were measured in a two-minute sitting position. After the tasks, the values were recorded for another two minutes, also while sitting.

The electromyographic signals were measured from segments of the deltoid muscle (acromial, clavicular and spinal part) and the trapezius muscle (ascending, transverse and descending part) and from the biceps brachii muscle. This allows a detailed picture to be made of the activity of the shoulder muscles during a task. It was not possible to measure the triceps brachii muscle due the arm cuffs of the exoskeleton.

Measuring technology

Metabolic parameters

Oxygen consumption (O2 rate, breath-by-breath method) was measured using the mobile ergospirometry system MetaMax®3B (Cortex Biophysik GmbH, Leipzig, Germany). This measurement integrates the simultaneous recording of the heart rate with a sport tester T31 (Polar Electro GmbH, Büttelborn, Germany).

Electromyographic parameters

To measure the electromyographic parameters, a wireless Noraxon Telemyo DTS system (Noraxon, Scottsdale, AZ, USA; measuring frequency 1000 Hz) was used. Electrodes of the type Blue Sensor P (Ambu, Frankfurt, Germany) were used.

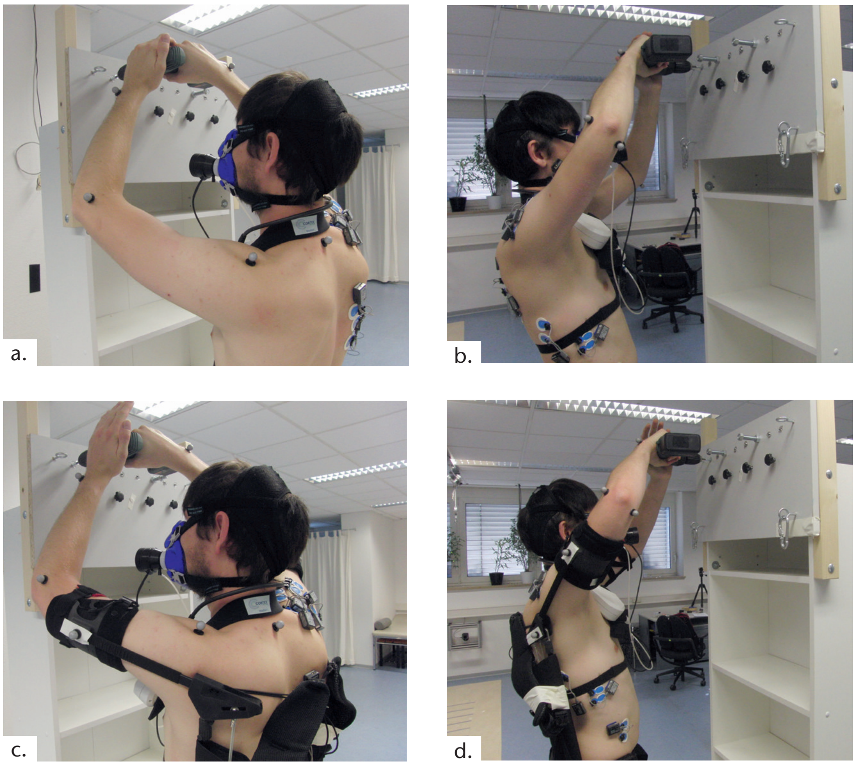

Fig. 3 Execution of the work task without (a,b) and with (c,d) exoskeleton

Data processing

Metabolic parameters

To determine the resting values (oxygen consumption and heart rate), all values for the last minute before performing the measured task were averaged. The mean values for the last minute, i.e. in the presumed steady state, were again calculated from the data for the 5-minute task. The data were collected again in the last minute of the final resting period. The described determination of parameters was used for the measurements with and without the exoskeleton. The values of all subjects formed the basis for calculating the group means for the two measuring situations.

Electromyographic parameters

The raw signals of the EMG values were rectified and artefacts (incl. "crosstalk" from ECG signals) eliminated using special algorithms [11]. The signal was then smoothed using an RMS filter (window size 100 ms). From the five-minute records, a mean amplitude was formed for every muscle as a basis for the group means for the two situations to be compared.

The muscle fatigue index (MFI) was determined to quantify muscle fatigue [12]. This index describes a shift in the mean frequency of the electromyographic signal toward lower frequencies when a muscle becomes fatigued under nearly static conditions. For this, the entire timeline of the raw EMG was divided into periods of ten seconds (P) and the mean frequency in each of these segments was determined. The increase in the regression lines that were calculated from the mean frequencies over time forms the numerical value of the MFI. The MFI is given as (s*P)-1. Negative values represent muscle fatigue.

Statistics

The non-parametric Wilcoxon test was used to check for differences between the group mean values. Error probabilities of $p<0.05$ (significant difference) and $p<0.01$ (highly significant difference) were specified for the level of significance.

Results

Metabolic parameters

The resting values measured before and after loading show no significant differences for either oxygen consumption or heart rate with and without an exoskeleton. During the task, significant reductions of the heart rate by 7% and of oxygen consumption by 11% were measured when the exoskeleton was used (Fig. 4, 5).

Electromyographic parameters

The parameters derived from the mean EMG amplitudes yielded only significant effects; the effect size was muscle-specific. When using the exoskeleton, the mean amplitude was lowered for all segments of the deltoid muscle and the biceps brachii muscle between 40% and 48%, for the segments of the trapezius muscle between 18% and 34% (Fig. 6).

The muscle fatigue index MFI without an exoskeleton was between -0.44 and -0.62 (s*P)-1 for the segments of the deltoid and biceps brachii muscles and was lowered significantly for these muscles to levels between -0.08 and -0.21 (s*P)-1 when the task was performed with an exoskeleton. The MFI for the segments of the trapezius muscle without an exoskeleton was much lower than the other muscles analysed. With an exoskeleton, a significant reduction of the parameter was measured for the lower segment of this muscle (Fig. 7).

Discussion

The aim of this principle study was to investigate the biomechanical effect of the Paexo exoskeleton in a laboratory setting that is similar to actual working conditions using objective measuring methods. In occupational medicine, (surface) electromyography is the standard method for testing strain and fatigue in individual muscles [13]. Under defined conditions (loading intensity not in the maximum range and duration not more than around 30 min), the measurement of oxygen consumption can be an indicator for metabolic energy consumption [14]. Together with the heart rate, oxygen consumption is thus a measure of the overall stress to the organism from non-maximum work, characterised from the physiological perspective by reaching a steady-state level [15].

The non-significant differences in the resting values for the metabolic parameters prove that the breaks specified in the trial design resulted in complete recovery of the subjects, thus allowing reliable comparisons of the tasks performed. The lower values for heart rate and oxygen consumption measured when using an exoskeleton correspond to a reduction in the overall stress to the organism, which was determined in an earlier study in a similar way [16]. The strength of the effect, which is clearly positively perceptible for the user of the system [16], has been proven in this magnitude, for instance for orthoses, only in comparisons of components with widely differing functional principles [17, 18].

The electromyographic parameters document clearly the drastic reduction of the user's muscular strain when using the exoskeleton. The results correlate with findings of other studies that demonstrate similar effects for individual muscles in the shoulder region [16, 19]. In this study, the complex measurement of several muscle groups makes it clear that the reduction of muscle strain is most pronounced in the segments of the deltoid and in the biceps brachii muscles. Because the two tasks were also performed in comparable joint angle positions (Fig. 3), the findings allow the conclusion in the sense of a plausibility assessment that the required muscle forces are considerably reduced, especially in the deltoid muscle [20]. One result of reducing muscle forces is the reduction of the internal joint compression forces, which could lead to fewer symptoms of wear anticipated over longer periods [20, 21].

When analysing the values for the muscle fatigue index, it must be noted that determining the MFI is valid for static conditions [13, 23]. The task studied here can be described as nearly static. The reduction of the MFI, equivalent to a drastic reduction of the local muscle fatigue when using the exoskeleton, was, in turn, muscle-specific (strongest effects in the deltoid and biceps brachii muscles). The reduction of the MFI also correlates with the metabolic values as, under aerobic energy supply processes, reduced oxygen consumption is a measure for the lower oxygen supply required for the skeletal muscle [14].

Conclusion and outlook

The results show that, in principle, the use of the exoskeleton tested leads to a reduction of strain in the shoulder region supported. The effect,

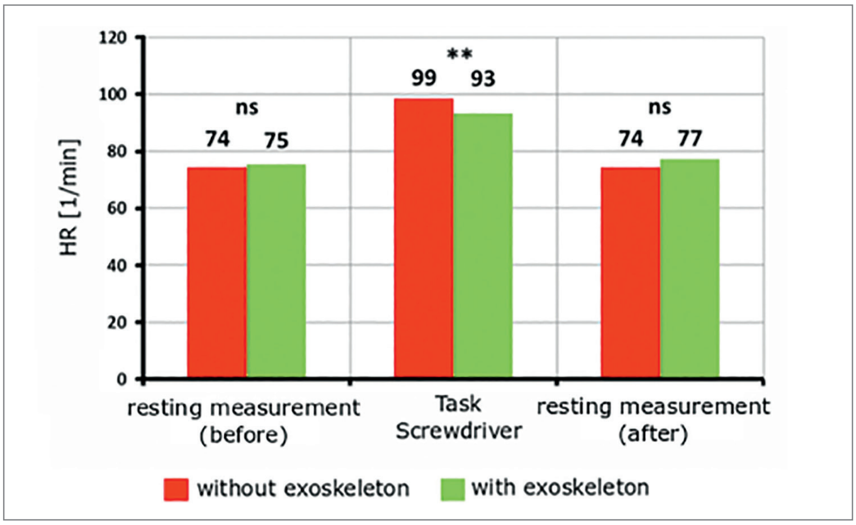

Fig. 4 *Mean values of heart rate (HR) for resting measurements and work task with exoskeleton (green) and without exoskeleton (red), ns - not significant, **: significant difference with p<0.01, WILCOXON Test, p-level of significance*

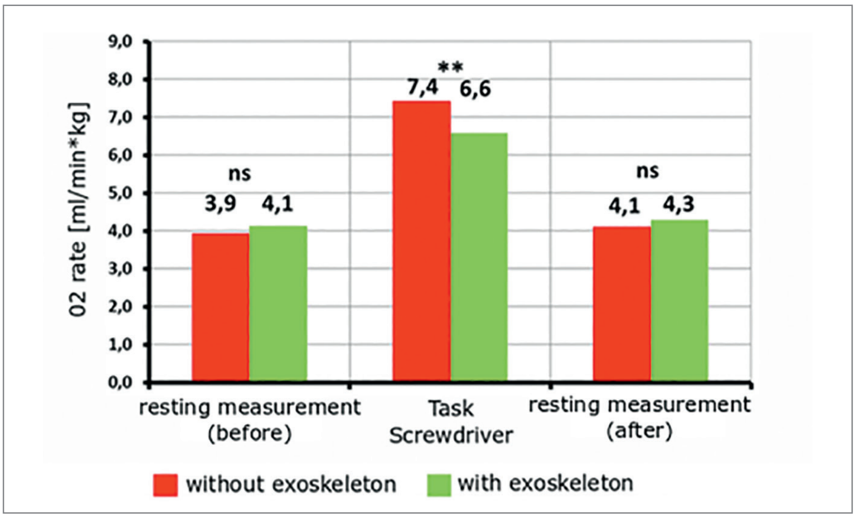

Fig. 5 *Mean values of oxygen consumption (O2_rate) of resting measurements and work task with exoskeleton (green) and without exoskeleton (red) ns - not significant, **: significant difference with p<0.01, WILCOXON Test, p-level of significance*

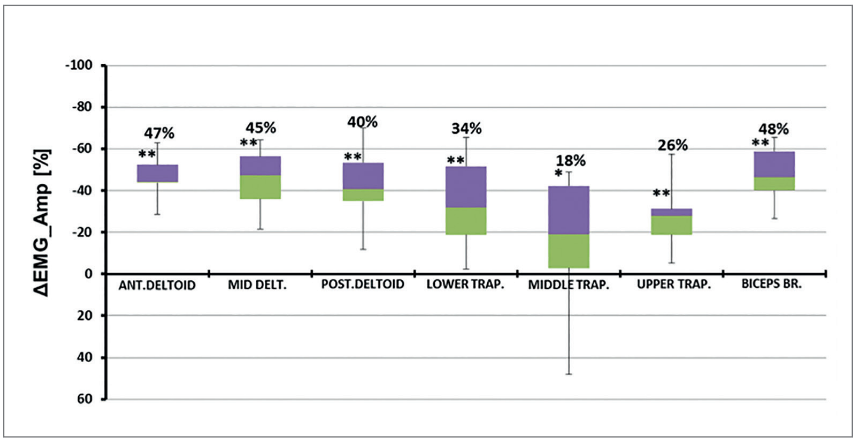

Fig. 6 *Average percentage change of the mean EMG amplitude (ΔEMG_Amp) during the work task using the exoskeleton in comparison of the two situations (negative sign: EMG amplitude decreases by using the exoskeleton; *, **: significant difference with p<0.05 or p<0.01 WILCOXON Test, p-level of significance)*

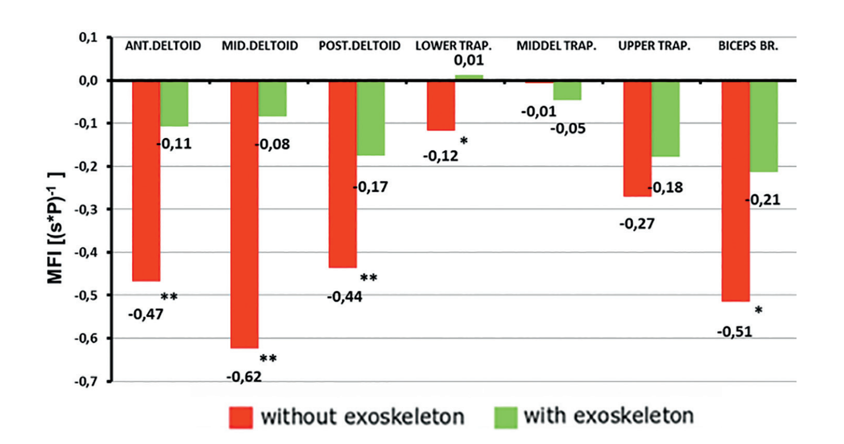

*Fig. 7 Mean muscular fatigue index (MFI) during the work task in comparison without exoskeleton (red) and with exoskeleton (green), ns: difference is not significant, *, **: significant difference with p<0.05 or p<0.01, WILCOXON Test, p-level of significance)*

which was also directly perceived to be positive, is thus associated with high user acceptance. In order to test whether this strain reduction can be assumed as applicable to complex cases and varying user groups, further scientific studies with different groups of subjects and in the form of field tests must be conducted in the future. Today's level of knowledge and research does not allow any reliable statements to be made regarding a general long-term positive effect on health by reducing strain and redistributing forces in everyday working life [23]. This also underlines the need for further systematic studies. This would also ensure that new information could flow into the future development of industrial exoskeletons. The dialogue with users, occupational scientists and manufacturers is essential. The primary aspect here is to ensure the health of users by meeting their needs as far as possible in order to achieve optimal user acceptance.

Corresponding author:
Dr. Thomas Schmalz
Ottobock SE & Co. KGaA, Clinical Research & Services / Biomechanics
Hermann-Rein-Straße 2a,
37075 Göttingen
Tel.: 05513075131,
schmalz@ottobock.de

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