Field Study to Objectify the Stress and Strain on Male Workers During Car Wheel Changes in the Course of Using an Active Exoskeleton

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Abstract. The aim of a field study was to prove whether the expected relief of the musculoskeletal system occurs when an active exoskeleton is used. For this purpose, the seasonal changing of car wheels was chosen as a work task. The active exoskeleton Cray X was used. The physical stress and strain of 10 professional workers during the wheel change was determined by measuring the heart rate, analyzing the work pulse and the energy expenditure. In addition, a survey was conducted with 20 employees to determine the physical stress in different body regions. When comparing the work performed with and without the exoskeleton, no significant difference was measured for the heart rate. The difference in the work pulses was only 2 beats per minute. The wheel change with active exoskeleton required an energy expenditure of 1073 kJ/h. When carried out without exoskeleton, only slightly reduced values for the energy expenditure (1066 kJ/h) were registered. However, the objectively undetectable relief is subjectively felt. The strongest differences of the different application scenarios are found for the lower and upper back (25% and 21% respectively) and for the lower and upper trunk (11% and 7% respectively) in favor of exoskeletal application. Nevertheless, it must be concluded, active exoskeletons cannot fundamentally protect the employee from medium and long-term musculoskeletal disorders by physically supporting the execution of movements.

Keywords: Manual material handling · Active exoskeleton · Ergospirometry · Heart rate · Subjective assessment

1 Introduction

In order to be able to make physically strenuous work in particular less stressful for the employee and thus hopefully also healthier, the use of active or passive exoskeletons is increasingly being evaluated in laboratory and field studies. Field studies on active exoskeletons are however still rare. Exoskeletons are supposed to relieve the hand-arm-shoulder system and the back, especially during handling procedures. Musculoskeletal complaints and diseases in these body regions represent a significant societal problem with a high burden for the health care systems, the economy and the affected persons themselves [1]. A causal relationship is hypothesized between, on the one hand, high and

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frequent force applications, repetitive activities, static muscle strains and, on the other hand, musculoskeletal complaints and diseases [2]. The passive and active support systems are now considered as an opportunity for prevention [3, 4]. The key operating principle of these assistive systems worn directly on the body is to transfer mechanical energy to the human body, thereby reducing physical stress on defined parts of the body [5].

Exoskeletons can be differentiated according to the type of energy supply, the body region supported, and the degree of fit to human anthropometry [6]. Already widely used are passive exoskeletons. These are usually a support frame that returns the energy absorbed and stored during a movement to the user for stabilization or movement support [6]. At the current state of the art, it is mainly passive exoskeletons that can be used for an industrial application. Here, there have been a variety of developments worldwide in recent years that have improved weight, wearing comfort and manageability.

In contrast, an exoskeleton is said to be "active" if it has one or more electrical and/or mechanical drive elements, pneumatic or hydraulic cylinders that enhance the performance of a user's joint system. Active systems are often still much heavier than passive systems and have yet to go through the development process of passive systems. However, development progress is readily apparent and the first systems are marketable, such as the "Cray X" from German Bionics used in the field study.

The current use case assembly or disassembly and storage or supply of car wheels represents work tasks that expose people to physical stress due to increased physical forces and unfavorable postures. In order to be able to evaluate such loads and stresses, a comparative field investigation was carried out during a car wheel change using the active exoskeleton "Cray X". The evaluation focused on the question of the physiological benefits but also the possible risks of the use of an active exoskeleton during car wheel changes under field conditions.

2 Methodology

As part of the objective and subjective analysis of working conditions with and without the use of an active "Cray X" exoskeleton, a field study was conducted in an automotive workshop. Only the use of the measurement technology and the simulated test environment or test conditions created an adapted laboratory "microcosm". The experiments were performed under a controlled condition, i.e. without exoskeleton, and under an intervened condition with the use of the "Cray X" exoskeleton. The starting test condition was changed in a controlled manner for each individual subject. The allocation of the subjects to the trials and thus to the start condition was randomized to prevent learning and sequence effects. The average age of the 20 male car mechanics was 24.9 $\pm$ 8.21 years with an average height of 178.4 $\pm$ 6.98 cm, a weight of 83.9 $\pm$ 16.09 kg and a BMI of 26.29 $\pm$ 4.17.

The mobile ergospirometry system "Cortex MetaMax 3B-R2" was used for the recording of the relevant physiological parameters. The spirometry device measures physical respiratory parameters using "Breath-by-Breath" or "Intra-Breath" measurement technique in- and expiratory oxygen uptake as well as respiratory flow delivery. The aim is to determine the energy expenditure under real working and environmental conditions. Furthermore, the system was coupled with the Polar® S810i heart rate measuring system.

The work task consisted of a typical wheel change on a working platform. The work phase consisted of the following work acts:

- unscrewing and removing of a total of four passenger car wheels with subsequent storage on the ground,
- storing or stacking four separate wheels, which were also on the ground, in a loading area at a height of 110 cm,
- mounting of the four wheels previously placed on the floor,
- tightening the individual wheel nuts,
- depositing the previously stacked wheels.

After the tests were conducted, the strain experience was evaluated using a modified body map [7] with the aid of the standardized scale from 0 "no stress" to 10 "maximum stress" and statistically analyzed [8]. The body map was used to evaluate both the front side of the body with a total of twelve different body parts and the back side of the body with six different body parts. A high degree of standardization was used to ensure the comparability of the responses of the different subjects. In addition, the degree of reliability of the results from standardized questionnaire surveys is always higher than with less standardized methods of a survey. The ordinal scaled data were analyzed using the non-parametric Wilcoxon signed rank sum test. Statistical significance was assumed from a significance value of 5%.

3 Results

In order to objectify the stress and strain of working with an exoskeleton, the assembly of motor vehicle wheels was analyzed from an occupational science perspective. In addition to body posture, the work-physiologically relevant parameters "heart rate", "work pulse" and "energy expenditure" were recorded. In the context of the objective presentation of results, an analytical statistical evaluation had to be omitted due to the small sample size of 10 subjects.

During the assembly tests, a near-optimal posture was ensured for a large proportion of the test subjects, regardless of whether the support system was used or not. In addition to an upright posture, a vertical downward upper arm position, an angular position between the upper and lower arm greater than 90°, and a gaze and head tilt of approx. 30–35° were also required. The test subjects also assumed a body position aligned "frontally" to the work task. The feet were about hip-width apart and turned slightly outward. This position formed a "relaxed, upright standing position." The position of the back and the position of the center of gravity of the load to be carried or lifted also have a significant influence on human stress and strain. If lifting and carrying is done with a straight back and close to the body, the resulting pressure is transmitted evenly to the intervertebral disc. There was an increased risk of incorrect stress on the intervertebral discs, particularly when picking up or putting down the wheels. Figure 1 shows by way of example that the test subjects differed in their posture or behavior during lifting and carrying. The manual handling of motor vehicle wheels corresponds to the handling of medium-heavy loads at an increased cycle frequency when the weight of a wheel of a BMW Mini is around 22 kg. If back complaints and movement pain occur as a result, e.g. due to a bent back posture (cf. Fig. 1, left), as is unavoidable when wearing the active exoskeleton, these lead to incorrect and relieving postures. This inevitably results in tension and further incorrect strain and damage to the intervertebral discs. Even with low load handling, it is important to reduce the prevailing compressive forces to a minimum with the aid of short lever arms, for example by lifting the wheels with the back or spine in a straight position from the knees, as can be seen in the right-hand illustration in Fig. 1.

Fig. 1. Body postures while picking up a wheel with (left) and without active exoskeleton “Cray X” (right).

The average time required to perform the work task is higher with the exoskeleton (37.85 s/work cycle) than without the support system (34.4 s/work cycle). The work pulse profiles measured in the tests show that both the storage and retrieval of the light alloy wheels weighing approx. 22 kg and the actual assembly and disassembly can be described as a physically demanding activity.

The average increase in heart rate without using the exoskeleton is 45 beats per minute (bpm). Although the heart rate “only” reaches 43 bpm when using the exoskeleton, both values are above the endurance level of 35 bpm compared to the resting heart rate measured in a sitting position. The average resting heart rate was 73 bpm (with and without exoskeleton). It should be kept in mind that the heart rate response to a given load depends on several influencing variables. In this context, it is important to note that every person experiences a decrease in maximum heart rate per year of life with increasing age. However, for the relatively young subject collective with an average age of 25.4 years, no problem with cardiac workload was yet to be expected. This is also shown by the calculations. The average heart rate was in relation to the maximum possible workload 61% when using the exoskeleton and 63% when not using the exoskeleton, and was therefore in the uncritical range.

After the presentation of the results of the work physiological parameter, which represents the strain side of the work, the energy expenditure represents the quantity with which the stress and thus the severity of the physical work can be characterized in a numerical value. The most important spirometric parameters include oxygen uptake, which averaged over all work subjects was 1.14 l/min when using the exoskeleton and 1.13 l/min without using the exoskeleton. The respiratory quotient was calculated from the oxygen uptake and the carbon dioxide output for both test scenarios in order to determine the energetic equivalent. The product of the energetic equivalent and the oxygen uptake per hour results in the gross energy expenditure.

In favor of a detailed comparison, gross energy expenditure must be broken down into basic energy expenditure and work energy expenditure, which depend on age, height and body mass. The latter represents the load experienced during work. The basal metabolic rate for an average age of 25.4 years and according to the Mifflin-St. Jeor formula [9] is 322 kJ/h or 89 W. Taking into account the efficiency of humans, which according to [10] is 5–10% in industrial activities, with a power input, i.e. work energy expenditure, of 1073 kJ/h or 298 W during the use of the "Cray X", at best 30 W were invested in the actual work task.

When the test was performed without an exoskeleton, only slightly reduced values were registered for the work energy expenditure (1066 kJ/h, 296 W). With just under 270 W, a considerable heat surplus was produced, assuming an average temperature or room temperature. With the help of respiratory parameters, different degrees of utilization of the entire cardiopulmonary system as a functional unit consisting of heart and lungs can be determined – similar to the degree of utilization of the heart for determining age-dependent strain. For this purpose, the oxygen uptake is set in relation to the maximum oxygen uptake, which defines the physical performance limit of the cardiopulmonary system [11]. The maximal oxygen uptake can then be calculated according to [12]. Thus, the subject collective can take up a maximum of about 3 l/min of oxygen. The degree of utilization of the cardiovascular system accordingly amounts to approx. 40% when using the exoskeleton, while a degree of utilization of 38% is recorded without support.

In order to be able to comparatively analyze the working conditions in the course of a motor vehicle wheel change when used with and without an exoskeleton, an important component of the holistic occupational science analysis was not only the objectification of the entire cardiopulmonary system, but also a personal statement by each individual test person regarding the subjectively perceived strain.

As the objective results already showed, the wheel change causes an increased physical strain. The assessment of the test subjects confirms this finding. The respondent collective now comprised 20 subjects with an average age of 24.9 years, whereby one subject had to be excluded due to missing information. In addition, individual subjects did not provide complete information, which reduced the sample for individual parameters. While only the neck and the buttocks caused a weak to moderate strain, the remaining parts of the body experienced a consistently increased strain. Upper and lower back, upper arms as well as knees and thighs experience a stronger (>6) and overall strongest strain on the scale from 0 to 10. The subjectively perceived additional strain is lower for the entire shoulder area, the trunk, the hips as well as for the back when using the "Cray X" than without its application. Only the upper extremities (with the exception of the elbow) as well as the neck and the feet register an additional strain during exoskeleton use, but these are marginal compared to use without support. The strongest differences of the different application scenarios are found for the lower and upper back (25% and 21% respectively) and for the lower and upper trunk (11% and 7% respectively) in favor of exoskeletal application (cp. Figure 2). The differences are significant for the upper ($z = 2.79$, $p = 0.005$, $n = 17$) and lower back ($z = 2.82$, $p = 0.005$, $n = 18$). While the activity without the use of the support system – especially for the lower back – is evaluated approximately as a very strong strain, the same task with the help of the exoskeleton is only "strenuous" from the subjects' point of view. If only the ten subjects from whom objective data were generated are considered in the context of the subjective feedback, the results are approximately confirmed in comparison to the entire collective.

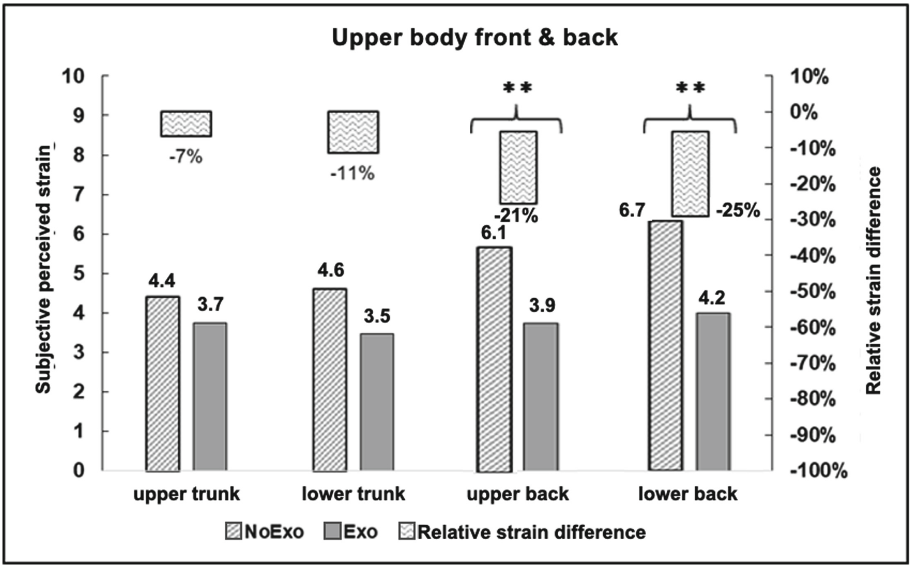

Fig. 2. Assessment of perceived strain in the upper and lower trunk as well as upper and lower back in the course of the work task. Mean values over 20 test subjects.

4 Discussion

The "Cray X" was specially designed to reduce the compression pressure in the lower back area when lifting heavy loads. If a manual handling with straight back is performed without exoskeleton and loads are lifted and carried close to the body, the pressure is evenly transferred to the intervertebral disc. In this case, the weight of the load and one's own body has only a relatively short lever arm to the spinal column. However, it has been shown that even basic ergonomically correct behavior, such as a straight back or lifting from the knees, is not fully maintained. When transporting the wheel, it is also difficult to carry the object, which weighs around 22 kg, close to the body due to its design, and postural work is therefore required. Overall, the partial processes can lead to compensatory hyperlordosis, i.e., discomfort in the back region or lumbar spine. Due to the increased demand for oxygen and the worsened blood circulation, the cardiovascular strain increases in addition to the muscular strain. All activities, including the assembly and disassembly of the wheels, are performed in a standing position. The employee is thus exposed to an increased energy expenditure during the entire work performance.

These findings are largely confirmed by the objective results. The work to be performed is individually connected with considerably less effort when using the "Cray X". However, the most expected support during the stacking or removal of the wheels with the help of the exoskeleton could only be proven to a limited extent. The objectively obtained data show slightly reduced values for the heart rate when using the exoskeleton. The energy expenditure is even marginally higher when using the "Cray X" than without. The weight of 8 kg of the exoskeleton contributes to this.

If a repetitive or high-frequency execution of the work task is assumed, the exoskeleton can thus generate physiological advantages for the user in the form of a reduction of the compression pressure in the lower back area. This finding is significantly confirmed by the subjectively perceived strain on the test persons, in particular by the fact that reduced strain on the back, trunk and hips was noted by using the active exoskeleton. In total, however, there is only a slight advantage in handling the wheels.

5 Conclusions

To what extent the activity analyzed here represents the fitting application scenario for an active-assistive exoskeleton is doubtful. After evaluation of the data, an overall view shows that only marginal differences were recorded. Only the pick-up and the setting down of the wheels was measurably and noticeably supported by the exoskeleton. However, this support is only really effective if the body posture without using an exoskeleton is not ergonomic, i.e. with legs stretched out and back bent. Irrespective of the application and implementation of such a support system, it seems sensible to inform employees about possible risks resulting from unfavorable postures and to provide them with comprehensive training in the areas of load handling and standing workplaces. A workplace analysis and an associated assessment of the implementation of exoskeletons are indispensable in order to generate efficient workplace conditions that minimize stress.

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