Exploratory Pilot Study Investigating Effects of Exoskeletons on Movement Patterns

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Abstract

The ergonomic configuration of processes is becoming increasingly important, especially considering the changing demographics and increasing shortage of skilled workers. Exoskeletons are widely discussed as a means of protecting employees from overstraining at the level of personal protective measures. The field of industrial exoskeletons research is still relatively new and has many unanswered questions. For example, there have not yet been sufficient studies on the influence of exoskeletons on the movements of employees. This publication discusses the effects of exoskeletons in manual processes. For this purpose, exemplary physical activities are carried out in a pilot study by a subject collective, whereby the tasks are executed with and without an exoskeleton. During the execution, a motion capturing system is used to record the movement data. Different back-supporting exoskeletons are taken into account in the study. The evaluation is based on the joint angles of the participants while performing tasks with and without exoskeletons. It is shown that the use of exoskeletons has a significant effect on the movement patterns, with a distinction made between rigid and soft support structures.

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Keywords

Exoskeletons • Movement patterns • Motion capturing

1 Introduction

Musculoskeletal disorders (MSDs) are the most frequent cause of physical functional limitations, chronic pain, and loss of quality of life worldwide, regardless of age group [1]. MSDs are a leading cause of lost work days and high healthcare costs in Germany [2, 3]. In particular, men engaged in manual tasks in production and logistics have a high risk of work incapacity [4]. Against this background and in view of demographic change, ergonomic work system design is becoming increasingly important as a preventive tool for the long-term protection of the ability to work [5, 6]. Conventional methods often reach their limits in this regard. Not all activities, especially not those with low production runs, manual tasks that change location, and large components, can be technically or economically sensibly automated [7, 8].

Exoskeletons (Exos) are considered to offer a high economic potential to reduce employee absenteeism through improved ergonomics [9] and to increase productivity [10]. Early studies indicate that work can be performed for longer periods without discomfort [11] and the reduction in effective handling weight can shorten execution times [12].

The present study examines the impact of industrial exoskeletons on human movement behavior during various typical industrial tasks, for which the use of Exos is often considered to have potential. Movements during activities with and without support, as well as with rigid and soft support structures, are compared. The conducted pilot study is understood as a preliminary experiment, which will precede a detailed investigation.

2 State of the Art

Movement patterns are defined in many different ways. In the context of logistics tasks, they can be defined as a standardized and consistent sequence of coordinated muscle contractions at one or more joints during work tasks, which is unique to each person [13, 14]. Especially in the context of manual production and logistics, movement patterns with high stress levels occur. Repetitive movements, especially those under load combined with ergonomically unfavorable bending and twisting movements, tire the body and promote physical injuries. An example of activities with a high repetition rate, forced postures and frequent lifting and lowering movements is order picking, where pain and musculoskeletal disorders often occur as a result of one-sided stress.

The effect of the use of Exos has already been investigated in studies. However, these studies mainly focused on the areas of performance [15] and biomechanical parameters [16]. Thus, studies have demonstrated a positive effect of Exos on physiological demands [11, 16, 17]. Previous studies have investigated restrictions in the freedom of movement caused by Exos via subjective queries [6, 15] or have used a combination of recorded movement data and EMG measurements to assess changes in physical strain [16]. Despite the relevance of possible movement restrictions due to the additionally handled weight as well as the support structure, the movement behavior of the employees is hardly investigated separately in current research [18].

Industrial Exos represent a personal protective measure for the employees and are understood as an external support structure that mechanically supports certain body segments [6]. Depending on the activity, Exos can provide targeted support for different body regions. Load reduction in the areas of the hands and arms, for example, is useful for overhead activities. In contrast, support of the trunk is advantageous for load handling and static posture work [19]. Furthermore, Exos can be divided into active and passive systems [20]. In contrast to active systems, passive exos have no external energy sources and use only stored energy (e.g. springs or gravity) that is charged by the user [21]. Passive systems can be further divided into rigid Exos with dimensionally stable structures for force transmission, and soft Exos with textile elements that transmit forces [22].

3 Concept and Procedure

The study presented below serves to investigate the influence of Exos on movement patterns. Therefore the investigation is based on five representative processes with typical industrial loads.

3.1 Selection of Activities and Definition of Hypotheses

Studies (e.g. [6, 23]) report that production and logistics workers often suffer from MSDs due to the physical work involved. Despite the automation of several work processes, manual tasks characterized by forced postures and repetitive load handling make up a high proportion in both manufacturing and logistics [24]. Therefore, manual subtasks, which on the one hand cause high stress for production and logistics employees, and on the other hand occur frequently in production and work processes, were selected for the pilot study. Therefore, especially the lifting and carrying loads is strongly represented; typical work tasks include loading and unloading as well as order picking in production and assembly [25]. These activities have a highly effect on the lumbar spine. The more often a load has to be lifted and the heavier it weighs, the higher the risk of complaints in the lower back area [26]. In addition, other factors such as the lifting technique, the posture adopted, the type of load handling (one or two-handed), and the restriction of the range of motion can be identified as relevant. Specifically, forced postures can also lead to negative consequences such as muscle tension and pain in body segments.

On this basis, five activities are defined as representative test scenarios. The execution serves to identify potential influences of Exos on the movement patterns of the participants. Following the definition of movement patterns, the joint angles assumed by the participants during the execution of the tasks serve as evaluation parameters for hypothesis testing. The variables used for hypothesis testing are the flexion of the knee and hip joints, the flexion and axial rotation of the vertebral joints L5S1, L4L3, L1T12 and T9T8, the flexion of the ergonomic angles from upper arm to upper body (T8-Upper Arm) and the flexion of the ergonomic angles from upper body to pelvis (Pelvis-T8).

Lifting loads. The participants stand upright at a floor marker and bend forward to a mass. They pick it up at a height of 50 cm and bring it to 110 cm (final hand height). They turn their upper body 90° to the right and place the mass on a roller conveyor at the same height. The mass is then pushed out of the working area with the left hand and the participants return to their starting position. Whereas the specification for the process included the sequence of movements, each participant was free using a freely selected but always identical lifting technique. The experimental setup for this process is exemplified in the following Fig. 1.

Carrying loads. The participants lift the mass in the same way as in process one. After lifting, they turn 90° to the right. They walk unhindered a straight distance of 6 m, turn around and return to the starting point. After a 90° turn to the right, the participants set the mass down at the starting position.

Fig. 1 Experimental setup for lifting loads with floor marking for the starting position

5-Min Waist-Height lift task. The participants have the task of lifting a mass to waist height as often as possible within a period of five minutes, whereby the participants can take breaks independently. Lifting and setting down is performed in the same way as task one and two from a pallet; there is no torso rotation.

Loading a mesh box. The participants pick up a mass at waist level, turn 180° to the left and place the mass in an open mesh box. Due to the spatial restriction of the mesh box, the upper body is slightly bent forward and the mass is extended in front of the body. After placing the mass at a height of 60 cm (final hand height), the participants straighten up and turn back to the starting position.

Sorting small parts in forced position. The participants bend their upper body over a work surface at knee height for a period of five minutes and perform a sorting task with small parts. The flexion is not interrupted during the test.

3.2 Technical Systems

Two passive Exos are considered in this study, as shown in Fig. 2. On the one hand, the Exo Paexo Back (PB) from Ottobock SE & Co. KGaA as representative for a system with rigid support structure and the Exo LiftSuit (LS) by Auxivo AG as representative for textile, soft Exo. Both Exos have been sold commercially since 2020 and mainly support the user's back and trunk. In order to prove an influence it is necessary to determine the joint angles during the execution of the activities. For this purpose, motion data acquisition is performed using the Xsens-MVN-Awinda system from the Dutch supplier Xsens Technologies B. V., which records the participant's body movements with 17 inertial sensors at a sampling rate of 240 Hz. The data is translated into a biomechanical model of 23 body segments connected by joints [27], while taking into account anthropometric variables such as the participant's height.

In addition to the recording of objective parameters, subjective parameters are recorded by questioning the participants. The perceived difficulty of the task, local and general discomfort and perceived movement restrictions as well as a general assessment of the support systems used are queried as parameters. All parameters are assessed by the participants using the Visual Analog Scale (VAS), which is used to evaluate subjective parameters, e.g. in medical studies to classify the sensation of pain [30].

3.3 Procedure

The study took place from May 2 to May 18, 2022, at the training center of the Institute of Production Systems at TU Dortmund University, with one to two participants take part in the data acquisition per day. The duration of the test is a maximum of three hours.

Fig. 2 Illustration of PB (left) and LS (right), view of the back (acc. to [28, 29])

Beginning with the questioning about anthropometric and personal data, the examination of the exclusion criteria takes place. This is followed by the introduction to the study procedure. Each participant runs through the defined scenarios both without Exo and with both support systems, randomizing and balancing the order of support used to eliminate fatigue and potential interference effects.

After the application of the motion capturing system, the application of the corresponding Exo takes place. This is followed by the execution of the examination scenarios, whereby the activities are run through in the following order: Five times lifting loads, once sorting small parts in a forced posture, once loading a lattice box, three times carrying loads and once lifting for time. After each scenario has been carried out, the subjective parameters are queried by a questionnaire. After a complete series of measurements with an Exo, a query is made for the general evaluation. Between the series, there is a recovery break of five minutes plus the time required to change the Exo (approx. 15 min).

4 Results and Discussion

The described experimental procedure is run through a test collective in randomized order to exclude fatigue and possible interference effects. The study population consists of twelve participants with an average age of 27.9 years, half of whom are women

(29.8 years) and half men (26.0 years). Exclusion criteria are defined as functional limitations of the extremities and general physical complaints. Due to the limited adaptation possibilities of the technical systems, the body height is defined as 1.60–1.90 m, with an average body height of 1.75 m. The majority of the participants are located in the student environment and do not perform manual activities on a regular basis.

4.1 Objective Data

The basis for the objective analysis of the movement patterns is provided by the recorded movement data, for which an initial plausibility check is performed using video recordings made in parallel with the measurements serve. Subsequently, in a first step, the maxima and minima of all participants and test executions for the described activity are determined.

In order to reduce the target variables to be considered, an examination for correlation takes place. Thus, the examination of the vertebral joints shows that the vertebral joints L5S1, L4L3, L1T12 as well as T9T8 have a strong positive correlation ($r > 0.975$) for all activities in the presented study, which is why it can be limited to a consideration of the vertebral joint L5S1 as a representative variable for the hypothesis testing of the vertebral joints. A comparable study for the hip joints shows that the angles for the left and right hip joint only show a strong positive correlation ($r > 0.81$) for the activities of lifting loads, sorting and lifting for time. For the other activities, as well as for the angles of the knee joints, no relationship can be determined. With regard to the ergonomic joint angles, only a weak correlation can be found in each case. An exception is the flexion and extension of the upper arms in relation to the T8 vertebra. For activities with strong arm flexion (carrying loads, loading a lattice box as well as lifting for time), T8-Upper Arm right can be determined as a representative.

Following the correlation test, multiple regression models are set up to take into account the general conditions of Exos, activity and gender. Including the interactions of the three conditions as well as a normally distributed error variable, a regression model is obtained that is suitable for testing the established hypotheses in a post hoc model test. In this significance test, the mean values of the joint angles for the comparison of the Exo configurations are compared pairwise and examined for statistical differences. The significance level is defined as $\alpha = 5\%$, with an adjustment using the p-values.

In a consideration of the first activity, the adjusted exceedance probabilities listed in Table 1 provide statements about the hypotheses that were made with reference to the defined significance level.

The results show that the PB in particular has an influence on the movement patterns. With this Exo, an influence on the flexion of the back (L5S1) and the hip can be demonstrated for all participants, whereby a significant influence can also be demonstrated in the flexion of the knees and shoulder-arm for female participants.

Table 1 Results for max. joint flexion in “lifting loads” task with adjusted p-values

		p*-value						
		Knee joint		L5S1	Hip joint		T8-Upper arm	
		Left	Right		Left	Right	Left	Right
W/O versus PB	M	1.000	0.644	<0.001	0.021	0.006	1.000	1.000
	F	0.004	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
W/O versus LS	M	1.000	0.338	0.522	1.000	1.000	1.000	0.134
	F	0.016	0.040	1.000	0.001	0.394	0.097	0.033

A significant influence on the movement patterns can also be identified for the activity of carrying loads, especially for the PB. While the LS is only significantly expressed in the extension of the hip joints for female participants ($p^* < 0.001$), a gender-independent influence of the PB on the flexion of the hip ($p^* < 0.001$) as well as for female participants for the flexion of the left knee joint ($p^* = 0.016$) can be shown.

When examining the activity “loading a mesh box”, it can be seen that when lowering the load, significantly less flexion of the vertebral joints (represented by L5S1) ($p^* = 0.004$) can be identified by wearing the LS for female participants. In contrast, the effect of the PB is particularly evident in the axial rotation to the right in male participants ($p^* < 0.001$) and in the flexion of the hip in female participants ($p^* < 0.001$).

For the other activities, no influence on the movement patterns can be statistically demonstrated for the LS. For the PB, the effects are limited to male participants and relate to flexion of the upper body to the pelvis (angle pelvis-T8; $p^* < 0.001$) for “sorting small parts” and to flexion of the L5S1 ($p^* < 0.03$) for “5-Min Lift Task”.

4.2 Subjective Data

The participants were asked about the discomfort they felt during the performance of each activity. In addition, the participants were asked to compare the two Exos used with regard to perceived movement restrictions after all activities have been performed. The questions were answered using the VAS. Due to the small number of test persons, only a comparison of the frequency of statements was made, but not their severity.

With regard to the perceived discomfort, for example, a significant reduction in the area of the back is shown for the activity “lifting for a period of time” through the use of Exo. Here, for example, 8 out of 12 participants testify independently of the system that the perceived discomfort in the area of the back is significantly reduced. Similarly, at least seven participants testify to support in the lower back for the activity “carrying”, regardless of the specific system. For the activity “Sorting small parts in a forced posture”, however, a more differentiated picture emerges. Here, nine of 12 participants rated the LS

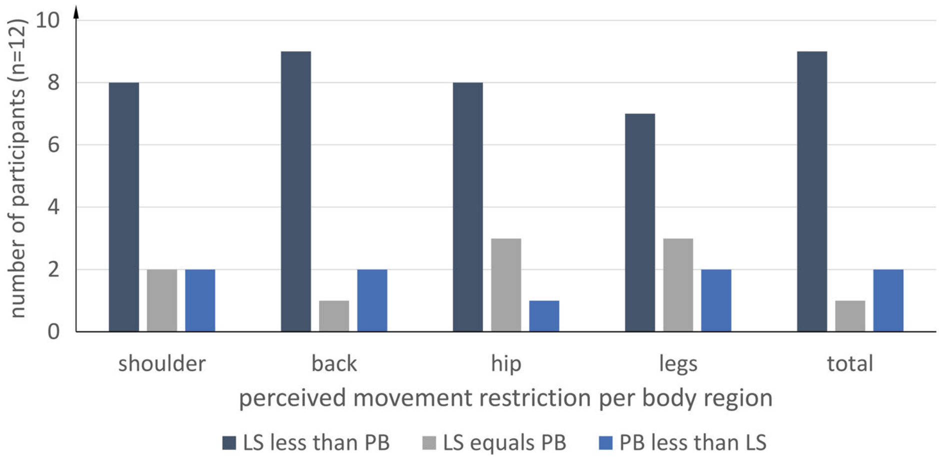

Fig. 3 Comparative representation of the participant survey on movement restrictions during the task "loading a mesh box"

as uncomfortable in the chest area. Likewise, 11 of the 12 participants rated the LS as more uncomfortable in the lower back.

If the results of the survey on movement restrictions are considered, it is noticeable that for all activities and all body regions, the movement restrictions exclusively with the PB were rated as higher by the participants than with the LS. An example is shown in Fig. 3 for the activity "Loading a mesh box".

4.3 Discussion

The analysis of the objective parameters confirms in principle the assumption that the use of Exos has an effect on the execution of movements in the test persons. It could be identified that the influence can be observed more strongly in dynamic load handling. For example, for compliance with static forced posture, only a small effect can be demonstrated.

In addition, it can be determined that in the comparison of both systems investigated as representatives for passive Exos with rigid and soft structure, differences in the influence on movement can be seen. Especially the PB with rigid structure shows a significant influence on the movement execution compared to the LS with soft structure.

In the context of the analysis of the subjective parameters, the basic suitability of Exos for reducing the perceived discomfort can be established. In particular, the systems have a significant effect in the area of the back. Regardless of the activity, however, the restriction of movement is perceived as higher exclusively by wearing the PB with rigid support structure.

5 Conclusion and Outlook

The findings obtained should be classified in that it is a study of a small sample of test persons and activities. However, it was possible to provide evidence that an influence of the supporting structure on the movement patterns of the participants could be demonstrated in both the objective and subjective parameters. The influence of Exos with rigid support structure could be identified as higher compared to systems with soft structure. At the same time, however, rigid structures were associated with less discomfort in movement performance than soft systems.

When interpreting the results presented, however, it should be noted that only the maximum flexion of the joint angles was used as a relevant evaluation criterion. The temporal course of the joints during the execution of the movement was not considered. In addition, it must be taken into account that the Xsens system calculates the movements in the lumbar region in particular based on only a few markers. This may affect the validity and accuracy of the target variables, which may be a problem in the case of small differences and adjustments of the movement patterns. Similarly, the results represent only a short-term investigation of processes; therefore, no statement can be made about long-term effects due to wearing the Exos on movement patterns.

Therefore, further investigations are needed to identify additional critical influencing variables and to increase the data base. Furthermore, the assessment of the ergonomic effects of the changed movement patterns should be considered in more detail in further studies, since the exclusive identification of a changed movement does not allow any statement about the ergonomic consequences.

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