Piloting the Use of an Upper Limb Passive Exoskeleton in Automotive Industry: Assessing User Acceptance and Intention of Use

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Abstract. The exoskeletons are being developed and recommended worldwide as wearable devices that could be used by workers exposed to demanding working conditions, such as overhead work. Many studies, designed for laboratory research, have been carried out so far and most of them came to the same kind of conclusions. With these findings it is expected that user acceptance (UA) and intention of use (IU) would not be a concern. This study was designed to assess UA and IU of an upper limb exoskeleton, Skelex MARK 1.3®, in a group of workstations, where technical and organizational measures implemented were not enough to reduce the exposure risk to overhead work and/or work above shoulder level, from an automotive industry assembly line. The exoskeleton was tested in 6 workstations, by 88 workers, during 4 consecutive weeks, since UA and IU are influenced by factors which only exist in real working scenarios.

Keywords: Passive exoskeleton · Upper limb exoskeleton · Automotive industry · User acceptance

1 Introduction

Currently, the layout of many industrial plants, particularly in the automotive industry, is designed as continuous production assembly lines with several workstations. In each workstation, a combination of processes is planned to be performed each working cycle. As this can occur hundreds of times (e.g. for 8 h shift with breaks of 14 min and cycle of 1.3 min, there are 358 working cycles) workers are exposed to the risk of developing work related musculoskeletal disorders (WMSD) and therefore organizations try to improve the working conditions using ergonomics intervention approaches. According to the occupational safety and health European legal framework, prevention strategies should be primarily based on technical measures and whenever needed combined with organizational measures. In this sense, ergonomic interventions are

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about changing the working conditions in such a way that job demand falls within an acceptable risk level for the development of WMSD. Nevertheless, in some circumstances, the desired technical measures cannot be implemented (e.g. to turn overhead work into work below head/shoulder by redesigning the conveyor system, since they can represent an investment of millions of euros) and the organizational ones are not enough to decrease the WMSD risk.

Since 2015, exoskeletons began to be used in the industry [1]. Although this technology is quite mature in the healthcare industry – with complex, energized, full body exoskeletons that assist with rehabilitation – there is limited availability of simple, useful exoskeletons for targeted applications such as in automotive industry. According to Voilqué and collaborators [2], 30 passive exoskeletons are available in the market but the most relevant for the automotive industry are the ones designed to assist workers while exposed to demanding working conditions such as manual material handling and overhead work. Therefore, for automotive industry the exoskeletons of interest are mostly to shoulder and trunk and specially from passive and semi passive types. A passive exoskeleton can be described as a wearable, external mechanical structure that can reduce the impact of a movement on the human body [3]. This is achieved by redistributing forces; thus, protecting specific body regions.

Upper limb support exoskeletons may be considered the most mature and replicated design [1]. By introducing exoskeletons in workstations, the change in user performance results not from additional physical strength, but from the ability to sustain strenuous positions over longer periods, for example working overhead [4].

Laboratory studies show that the use of exoskeletons decreases the biomechanical load by, for example, reducing by more than 40% the muscle load [1, 5, 6] and increasing performance by an average of 30% [7]. These advantages, identified in laboratory settings, are supporting the marketing of such devices. However, there is a risk for organizations to base their decision making regarding the introduction of exoskeletons in manufacturing processes only on such criteria. In fact, the physical effects of exoskeletons can influence the worker; therefore, user acceptance (UA) is an important factor to study [4]. Discomfort is one of the most important factors that can influence the UA and intention of use (IU), affecting the implementation success in industry [4]. Therefore discomfort, usability [8] and perceived effort [7] are also factors to study. Thus, if exoskeletons are to be used for a long time, UA and IU should be analyzed [4], and the tests should be performed in real work environment [4, 7, 8].

Study findings can be quite different depending if they are performed in laboratory or in a factory plant where noise, heat and production-driven stress cause participants to experience frustration more quickly [3].

Hensel evaluated UA and IU through a usability questionnaire [8]. Spearman's rank correlation coefficient indicated which variables correlated with acceptance and intention of use, and the Wilcoxon signed-rank test revealed which variable differs between the initial and final condition. The results were used to suggest improvements to the exoskeletons' design in order to adapt them to the workers' needs and to verify in which workstations the workers recognized the benefits of its use while performing the tasks.

Present study assessed UA and IU regarding the upper limb exoskeleton, Skelex MARK 1.3®, used in a group of workstations of an automotive industry assembly line, where previous technical and organizational measures were not enough to reduce the exposure to risk from overhead work and/or work above shoulder level.

2 Materials and Methods

2.1 Participants' Selection

The initial sample size was 122 volunteer workers. After the medical evaluation, 88 workers were selected. The participants' selection were based in the following criteria:

- Experience/Qualification - volunteers must have more than three months of experience performing the task (errors are more likely to occur when operators are in the learning phase; in the study it is important to exclude any factors that may cast doubt on whether errors resulted from the use of the exoskeleton);
- Medical restrictions – volunteers must have no medical restrictions to perform the task of the workstation defined for the use of the exoskeleton;
- Anthropometry - volunteers must fit the exoskeleton's adjustments range.

2.2 Tested Exoskeleton Characteristics

The Skelex MARK 1.3, illustrated in Fig. 1, is a wearable technology engineered to support the arms of workers in tasks above the shoulder/head level, made by SKELEX.

The exoskeleton weights 3.7 kg and consists of arm cups, arm cover, arm strap, flex frame, height adjustment, hip belt, hinge, hinge cover, cable, shoulder strap and a chest strap. The maximum lifting capacity is 4.0 kg per arm. The arm cups, arm strap, height, hip belt, shoulder strap and chest strap are adjustable. The range of adjustments is presented in Table 1.

Fig. 1. Skelex MARK 1.3

Table 1. Skelex adjustment range by body part

Body part dimension	Adjustment range (cm)
Shoulder width	43–54
Torso length	44–54
Pelvic circumference	84–124
Upper arm circumference	20–42

Before operating with the Skelex MARK 1.3, it is important to ensure that it is properly set in the workers' body. According to the manufacturer if worker's body part dimension is outside the range presented in the Table 1, Skelex MARK 1.3 does not provide a comfortable use.

2.3 Workstations' Selection

Exoskeletons are not suited to all types of workstations. Therefore, the selection of the workstations for testing the device was based on the criterion that more than 30% of the activity was performed above the shoulder/head level. The Ergonomic Assessment Worksheet (EAWS) method was used to identify such workstations.

Six workstations with a high percentage of work activity above shoulder/head level were selected: Tailgate wiring loom routing (workst. 1), EPB/Brake pipes connection (workst. 2), Noise shield tightening (workst. 3), Rear end fit (workst. 4), Tailgate pre-fit (workst. 5) and Tailgate trim panel assembly (workst. 6).

2.4 Testing Protocol

The first step was to present the exoskeleton and the test procedures in meetings with the teams working at the selected workstations. The workers had the opportunity to ask questions and after that, the volunteers signed an informed consent.

Before starting the pilot study, each volunteer was subject to an initial evaluation in the medical department, which issued a certificate that he/she had no restriction to perform the tests. On the first day of the test, the participants learned how to use and adjust the exoskeleton. The participants initially used the exoskeleton for 30 min, and in each new day this duration was increased by 15 min until a maximum of 2 h per day was reached. At the end of each period of exoskeleton use, the participants completed a questionnaire. After the first and the last use participants were requested to answer a different questionnaire aimed to assess the exoskeleton performance and user acceptance based on subjective indexes. After completion of the test period all participants were subject to a final evaluation in the medical department.

2.5 Survey Tool

As referred, two questionnaires were used: a daily questionnaire (completed after each usage, except the first and the last test days) and a usability questionnaire (completed in the first and in the last days of use). The daily questionnaire included four questions related with the main and the secondary tasks, asking if the workers perceived the use of the exoskeleton as helping or disturbing. The usability questionnaire gathered the workers' opinion regarding perceived effort, discomfort, perceived utility, perceived ease of use and intention of use. The workers also classified the perceived effort for each body regions, considering the work with and without exoskeleton. The classification was based on Borg rating of perceived exertion scale (RPE scale). The reported discomfort might refer to heat, pressure, perspiration, skin irritation, among others. The scale used to classify discomfort was "1 - minimum discomfort" to "7 - maximum discomfort", based on 7-point Likert scale. The user acceptance (UA) was investigated with three questions (Q1 - The features of the exoskeleton satisfy my needs, Q2 - The exoskeleton is easy to use, Q3 - The exoskeleton is easy to dress and undress). The one about perception of utility was based on the UMUX-LITE model. The other two questions were about perception of ease of use: the first concerns ease of use and the second refers to the ease of dressing and undressing, which consists of an issue that was considered important according to the usability of the equipment, related to its use in the workplace. The questions were based on the System Usability Scale model. The intention of use (IU) questions (Q4 - I would like to have access to the exoskeleton, Q5 - I would use the exoskeleton) were based on the Technology Usage Inventory model. An agreement scale was used to assess the perception of utility, ease of use and intention of use, based on the 7-point Likert scale, from 1 (Don't agree) to 7 (Totally agree). Both surveys were adapted from (Hensel & Keil, 2019). Also, in both questionnaires the participants could express their complains and/or opinions. The analysis of the comments was made by separating the different topics and checking the frequency with which they were mentioned.

3 Results and Discussion

Since the exoskeleton was used during the whole cycle time, the differences of performance were studied by asking the workers opinion regarding the ability of the exoskeleton to support the shoulder postures and movements during the main and secondary tasks. In workstation 1, 87% of the workers reported that the exoskeleton helped performing the tasks above shoulder level and 74% in performing other tasks. Considering the tasks above shoulder level as main tasks, and the others as secondary, the perception that the exoskeleton helped was less for the secondary tasks in all workstations, except workstation 5, as shown in the left columns of Table 2. In workstation 5 the participants didn't recognize the benefit of using the equipment due to the complexity and dynamics of the main task performed.

The usability questionnaire allowed assessing the participants intention of use. Table 2 (right columns) shows the percentage of participants who agreed that they would use the exoskeleton, considering the initial and final questionnaire. In all workstations the IU decreases. Beyond the perceived effort and discomfort, the parameters that could influence the results are the increase of the duration of the test and the period of usage.

Table 2. Daily questionnaire and Intention of use (IU) results

Work-station	Daily questionnaire results		Intention of use (IU) results	
	Participants agreeing that exoskeleton helped performing the task (%)		Participants agreeing to usethe exoskeleton (%)	
	Main	Secondary	Initial	Final
1	87	74	76	53
2	69	43	83	33
3	58	52	44	39
4	23	2	40	10
5	0	39	25	13
6	38	35	35	26

Through the application of Spearman rank correlation coefficient, the perceived effort and the discomfort in different body regions are correlated with the UA and IU in all workstations. The variables most correlated with the UA and IU are the shoulder perceived effort and the back perceived discomfort. Table 3 represent the questions where there is a strong correlation between the variables, in the different workstations. When the coefficient is negative it means that the higher the discomfort or perceived effort of using the exoskeleton, the lower the intention to use. The variables of UA and UI are positively correlated with each other, and the perception of effort and discomfort are negative correlated with UA and UI.

The Wilcoxon signed-rank test provides the differences between the initial and final conditions. In workstation 1 only the neck perceived effort was significant. In workstations 2 and 3 the back and low back discomfort were significant. In workstation 4 the neck, back, low back, and left shoulder perceived effort were significant. In workstation 6 the back, low back, core, arms and hip discomfort were significant. The difference between intention of use was significant in workstations 2, 4, 5 and 6.

Despite the general recognition of the exoskeleton support in the comments made on the questionnaires, the participants expressed several complaints and the most frequent were related with heat and limited range of motion. Workers also mentioned the relief felt when removing the exoskeleton due to its weight. Throughout the study, it was noticed that in addition to the variables under analysis (i.e., perceived utility and discomfort) the type of tasks also influences the user acceptance and intention to use.

Table 3. Spearman's rank correlation coefficient

Workstation	Shoulder perceived effort (ρ)	Back perceived discomfort (ρ)
1	Q1 (−0,7629)	Q1 (−0,5036)
2	Q4 (−0,6575)	Q2 (−0,6185) Q4 (−0,6799)
	Q5 (−0,6202)	Q3 (−0,8076) Q5 (−0,5954)
3	–	Q2 (−0,6024)
4	Q3 (−0,6321)	Q2 (−0,6660)
5	–	–
6	Q1 (−0,5995) Q5 (−0,6202)	Q1 (−0,6351)
	Q2 (−0,6140)	Q2 (−0,6338)

Based on the tasks' characteristics, it was found that the longer the tasks above shoulder and the static levels of the task, the higher is the perceived utility and the lower is the discomfort of using the exoskeleton. A priority matrix was created to map usage recommendations against the type of tasks involved in the workstation. Figure 2 depicts this, relating the perceived utility and the discomfort with the type of tasks, and the recommendation of exoskeleton usage. Figure 3 shows where each studied workstation lays according the type of tasks performed there.

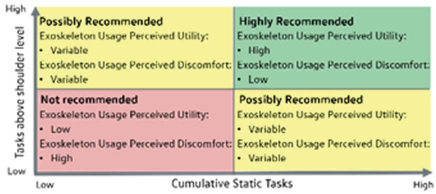

Fig. 2. Recommendation of exoskeleton usage according the type of tasks

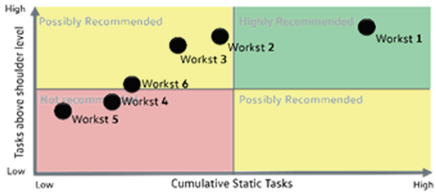

Fig. 3. Type of tasks performed in each workstation

Considering the cumulative static tasks that the workers elevate the arms above the shoulder level per cycle, workstation 1 is the only that is considered as recommended the use of the exoskeleton. However, several factors influence the user acceptance and intention of use, for example, heat, noise and stress. The Spearmans' rank correlation coefficient revealed that perceived effort and discomfort are negatively correlated with UA and IU, i.e., the higher the perceived effort or the discomfort, the lower is the UA and IU. The Wilcoxon test indicated that UA and IU can change and perceived effort and discomfort in some body regions also change over time and the length of usage duration. One reason might be due to organizational reasons, since participants could change the work shift, implying the non-use of the exoskeleton when scheduled. A second reason might be related with the existence of environmental conditions preventing a comfortable use of the exoskeletons (e.g., excessive heat). A third reason was volunteers evidencing symptoms of difficulties to perform the tasks, forcing the test to be stopped and requiring an evaluation at the medical department. This information was very useful, allowing the formulation of improvement proposals to the SKELEX.

4 Conclusions

According to the results, the workstation where the use of exoskeleton is most suitable according to the usability is workstation 1. Despite the fact that in five of the six workstations the use of exoskeleton was not recommended, it was deemed that applying some changes, suited to the needs of each workstation, the results of usability could change, and the exoskeleton usage may become recommended.

It was found that user acceptance and the intention of use tend to decrease over time.

Based on the comments made by the participants and the results obtained, it were proposed some improvements to the equipment, to make it lighter (after one hour of use, participants tended to report relief by removing the exoskeleton), to reduce or modify back and lower back area (the straps made pressure while performing some tasks and caused heat), and to increase the range of motion (participants need to perform various movements during work cycles and the exoskeleton restricted movement in some tasks). Once these changes are made, the exoskeleton will better meet the needs of the workers and UA and IU of the exoskeleton may increase.

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