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# Passive Upper Limb Exoskeletons: An Experimental Campaign with Workers

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**Abstract.** Wearable exoskeletons are currently evaluated as technological aids for workers on the factory floor, as suggested by the philosophy of Industry 4.0. The paper presents the results of experimental tests carried out on a first prototype of a passive upper limbs exoskeleton developed by IUVO. Eighteen FCA workers participated to the study. Experimental tests were designed to evaluate the influence of the exoskeleton while accomplishing different tasks, both in static and dynamic conditions.

Quantitative and qualitative parameters were analyzed to evaluate usability, potential benefits and acceptability of the device. Results show, on average, that wearing the exoskeleton has a positive effect in increasing: (i) endurance time while holding demanding postures with raised arms and/or having to lift and hold small work tools, (ii) endurance time and accuracy execution in precision tasks. The users also declared a lower perceived effort, while performing tasks with the exoskeleton.

**Keywords:** Upper limb exoskeleton · Human-robot cooperation
Usability

## 1 Introduction

An exoskeleton is a wearable robotic device, powered with passive or active systems, that allows limbs or trunk movement with increased strength and/or endurance [1, 2]. The type of actuation, the number of degrees of freedom and the body regions involved are extremely variable; hence, for the design of these devices it is necessary to target both the type of application and the users.

The robotic exoskeleton technology has acquired a rapid development starting from late 20th century with the advances in the technology in mechanical engineering, biomedical engineering, electronic engineering and artificial intelligence. The different existing exoskeletons, both commercial and laboratory prototypes can be classified considering the human body parts that are supported: lower body, upper body and full body exoskeletons. Furthermore, they can be divided into active and passive: the first


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ones have actuators to augment the user's power, while the latter use elements that store energy harvest by the wearer (e.g. mechanical springs, dampers, flexible materials) and return it during movements to assist in posture and to perform physical movements.

Quite recently the employment of exoskeletons has been extended from the rehabilitation [3, 4] and military field [5, 6] to the industrial setting [7–10]. This is in line with the philosophy of Industry 4.0, in which humans can be assisted by technological devices in difficult or unsafe tasks [11].

The research in industrial exoskeleton is still at an early stage; however, predictably exoskeletons can be useful when other preventive measures are not feasible or effective to lower workers' fatigue. Potential benefits of the introduction of exoskeleton as supporting devices in the industrial manufacturing environment are expected to increase worker's alertness, productivity and work quality; to support experienced personnel in the work force for longer; and to reduce work related musculoskeletal disorders.

Various passive upper limb exoskeletons have been developed in the last years for industrial applications. In particular, occupational tasks that require postures with elevated arms or overhead works, and hence represent a high risk factor for musculoskeletal disorders, are considered. Passive exoskeleton devices give a fixed contribution, independently from the external applied load. Usually they are designed to compensate, partially or totally, the gravity forces acting on the limb or on the trunk. However only few studies investigated effectiveness, usability, comfort, drawbacks and biomechanical strains associated to the use of upper limb exoskeleton in manufacturing tasks. Effectiveness, usability, comfort and drawbacks of the Levitate exoskeleton [7, 8] and of EksoVest [10, 12] are assessed in laboratory simulated operational tasks; an evaluation of the biomechanical strains, using electromyography, is presented in [10, 12, 13]. In [7, 8] the use of the exoskeleton shows a positive effect and on average there is an increase of the 30% both in duration and in quality of the performed tasks. However also some drawbacks associated to specific weight handling are disclosed. In [12] a drilling task was simulated: completion time decreased by nearly 20% with the exoskeleton, while in contrast precision decreased.

Both in [12] and [13] a significant muscle EMG activity reduction is recorded, when executing a task or handling a load. Also, no significant negative effects on the lower body are reported. However in [13] tasks were very short and the current prototype is not suited for industrial application.

Effectiveness, usability and comfort strictly depend on the design of the exoskeleton, but also on the tasks workers are required to perform. In this paper a first prototype of a new passive upper limb exoskeleton developed by IUVO [14], is tested. The new device was specifically designed for manufacturing uses, and it presents a reduced weight, a wearable, robust and compact design. Test campaign was intended to evaluate the effectiveness of the exoskeleton to enhance the duration of arm elevation in static posture and to assist the user in repeated arm elevation, with the same test designed proposed in [7, 8]. Tests were performed in the laboratory by automotive workers and they were designed to mimic manufacturing tasks.

## 2 Materials and Methods

### 2.1 Participants and Ethical Approval

Eighteen healthy male team leaders from Fiat Chrysler Automobiles Industries (FCA) volunteered to participate to the experimental campaign with the upper limb exoskeleton (Means ± SD: age 43.0 y ± 11.1 y; height 176.9 cm ± 5.5 cm; mass 77.3 kg ± 9.1 kg). All the workers had no limitation in strength or musculoskeletal disorders at the upper limbs.

Participants were completely informed about the nature of the study. All of them signed an informed consent and were free to interrupt the tests at any moment. The research methods and the protocols were standard and the measurements were performed in accordance with the declaration of Helsinki.

### 2.2 Exoskeleton Description

The exoskeleton, developed by IUVO [14], is passive and provides mechanical support to shoulders and arms, while forearms are not involved. The exoskeleton is worn similarly to a backpack (padded pelvis belt and two straps that go over the shoulders), as presented in Fig. 1. A metallic frame, paired with the trunk and the arms is present.

**Fig. 1.** Image of the exoskeleton worn by an operator during assembly tasks.

This first prototype of the exoskeleton, used in the test campaign, is consisting of:

- Human Interface: structure and materials that are in direct contact with the user's body. The main metallic structure comprises a T-shaped metallic frame for the core, with the transversal bar positioned on the back of the trunk in correspondence of the shoulders. On this bar are articulated two padded armbands that support the arms. In this way the metallic frame allows the transfer of the arm's weight to the trunk and pelvis, partially relieving arm, shoulder, neck and upper trunk muscles. Soft materials that are in direct contact with the body are removable and washable;

- Core technology: a mechanism composed of elastic elements that harvests energy and provides a variable assistive torque for the flexo-extension of the arm. The assistive torque has a peak at a flexo-extension angle of about 90°. The return of the arm to a neutral position is assured by the weight of the arm itself.

The exoskeleton assistance given to the users is adjustable and it was intended to support up to 70% of the user's arm weight. Furthermore, the adjustability is useful to suit different working tasks. Depending on the frequency of the upper-limb flexo-extension movements during the working cycle, the user may prefer a higher or lower level of assistance.

In order to fit the entire population, the exoskeleton has two available sizes: S/M, L/XL and each size can be further adjusted. Perfect fitting is mandatory to assure comfort, control and force handling.

### 2.3 Test Description and Procedure

All tests were led in Ergolab, Ergonomics Laboratory of FCA Manufacturing Engineering and they were performed similarly to what is extensively described in [7]. Tests were video recorded using a frontal and a lateral camera.

The experimental activities consisted of three different types of test to evaluate the contribution of the exoskeleton to assist in: (a) holding a static posture with extended arms, (b) repeated manual handling task and (c) performing precision task.

Tests were first performed without the exoskeleton and then with the exoskeleton.

Type of task and without/with exoskeleton conditions followed systematically the order reported above.

Moreover, at the end of the trials, semi-structured interviews were administered to the workers and rating scales were used to assess usability and user's acceptance of the device. All the tests and interviews were conducted in the same day for each participant. A short description of the tests is here reported, more details are stated in [7]:

(a) holding a static posture with extended arms

The test was designed to evaluate the potential benefit introduced by the exoskeleton on the onset of muscular fatigue during a demanding prolonged static action.

The worker was required to maintain a static posture: standing upright with extended arms (90° with respect the trunk) while holding a load (Fig. 2a), having a mass of 3.5 kg. The weight was placed on the forearm, so that the wrist was not involved.

The worker was requested to stop when feeling fatigue or discomfort.

(b) repeated manual handling task

The test was designed to evaluate the potential benefit introduced by the exoskeleton during a manual material handling activity vs. possible restriction to movements (e.g. frequent muscle contraction, shoulder abduction-adduction) [15].

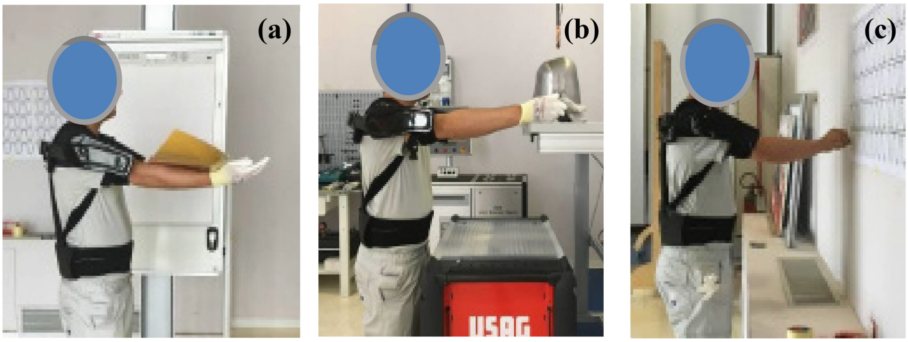


**Fig. 2.** Experimental activities wearing the upper-limb exoskeleton: (a) holding a static posture; (b) repeated manual material handling task; (c) precision task.

To simulate a real working task, the participant was requested to move an object with mass of 3.4 kg between two positions having different heights (Fig. 2b). Movements were paced at 30 action/min using a metronome.

(c) perform a precision task

The test was designed to evaluate the potential benefit introduced by the exoskeleton (lessen muscle strain, higher comfort rating and dexterity) during a precision task with significant static load on shoulder joint.

A sealing operation was simulated by asking to the participants to trace a continuous wavy line between two premarket traces, on a paper fixed on a billboard. The subject was standing, with his arm almost extended (Fig. 2c) and was not allowed to lower its arm, except at the end of the task. On the billboard, 5 wavy rows, having 27 arches each, were present and they were custom-placed at a different height with respect to the participant's shoulder. The end of the task was at subject's will or at the end of the premarket guides.

In Table 1 the main features of the tasks are summarized, in particular time duration and data collected are reported.

**Table 1.** Main features of the tasks

| Task | Aim | Task duration | Data collected |
|---|---|---|---|
| **(a)** Holding a static posture | Evaluate the potential benefit on the muscular fatigue during prolonged static action | At subject's will | • Maintenance time of the static posture<br>• Perceived exertion |
| **(b)** Manual material handling | Evaluate the potential benefit during a material handling activity vs. possible restriction to movements | 600 s or at subject's will | • Number of lifting<br>• Assessment of the pace<br>• Perceived exertion |
| **(c)** Precision task | Evaluate the potential benefit during a precision task with a significant static load on shoulder joint | End of the pre-marked guides or at subject's will | • Number of arches traced<br>• Precision score<br>• Execution time<br>• Perceived exertion |

### 2.4 Procedure

At the worker's arrival into the lab, the functioning of the exoskeleton was explained. He was also informed about the test protocol and that he could stop whenever he wanted, without completing the entire task or the whole protocol. Personal data and anthropometric measurements were also collected.

The participant was then asked to perform the static, repeated manual material handling and precision tasks without the exoskeleton. Between the tests, adequate time was left to the worker to rest.

The exoskeleton was adjusted to fit the user, it was worn and regulated.

The participant was then allowed to familiarize with the exoskeleton, before asking him to repeat the tests with the exoskeleton (Fig. 2).

The Borg Rating of Perceived Exertion Scale [16] was administrated to the participants to assess usability and acceptability of the exoskeleton. The subject was requested to quantify the intensity level of the activity at the end of each task, both without and with the exoskeleton.

## 3 Results and Discussion

Due to organisational glitches two workers did not finished the entire test campaign and hence they were discarded.

According to the main aim of the test, quantitative and qualitative parameters were analysed.

(a) Holding a static posture

Posture maintenance was controlled by visually inspecting the recorded video images and possibly, if this changed during the trial, the corresponding time was assumed as the end of the trial itself. In addition, a comparison of the postures without and with the exoskeleton was made, with particular attention to arms and the spine postures. No substantial differences were detected.

In Table 2 mean values and SD of the task duration with and without exoskeleton were reported. Also the time variation interval ($\Delta T = T_{EXO} - T_{NO\_EXO}$) and the relative variation ($\Delta T\% = (T_{EXO} - T_{NO\_EXO})/T_{NO\_EXO}$) were evaluated.

**Table 2.** Results of the static task

| | $T_{NO\_EXO}$ [s] | $T_{EXO}$ [s] | $\Delta T$ [s] | $\Delta T\%$ |
|---|---|---|---|---|
| Mean | 108.6 | 157.8 | 49.2 | 56% |
| SD | ±59.4 | ±76.1 | | |

The operators maintained the static posture for a mean time of 108.6 s and 157.8 s without and with the exoskeleton respectively, with a 56% relative longer time length in the second case. All participants, except one, increased their endurance time.

The average score of the Borg scale was 3 and 1.6 without and with the exoskeleton respectively.

(b) Repeated manual material handling task

In this trial, no operator went out of pace. However, in both conditions, without and with the exoskeleton, none of the participants accomplished the entire test duration (600 s), they all stopped before.

12 operators increased the endurance time when wearing the exoskeleton, while 4 decreased the time. The average score of the Borg scale was 3 and 2 without and with the exoskeleton, respectively.

These results suggest that no or minimal restriction to movements was introduced by the exoskeleton.

(c) Precision task

Also in this case posture maintenance, without and with the exoskeleton, was controlled by visually inspecting the recorded videos and no substantial differences were detected.

To analyse and quantify the performance obtained during this task, the wavy line was segmented into arches. The maximum number of arches to be filled was 135, distributed on 5 lines. In Table 3 the mean number of arches traced by each operator is reported without and with the exoskeleton.

To overcome the ceiling effect on the number of arches that the current task may present, also the average time necessary to trace the single arch was calculated. A significant increase of the number of traced arches and a decrease of the time execution for each arch can be observed when the workers worn the device.

**Table 3.** Results of the precision task

| | N° arches NO EXO | N° arches EXO | Time/arch NO EXO [s] | Time/arch EXO [s] | Δ N° arches | Δ% N° arches |
|---|---|---|---|---|---|---|
| Mean | 100.6 | 127.3 | 2.2 | 2.0 | 15.6 | 26.5% |
| SD | ±41.2 | ±18.1 | ±0.53 | ±0.51 | | ±30% |

Arches were then examined in order to assign a precision score. A full score of 10 was assigned to each arch, with an overall possible score of 1350. Four types of errors were identified based on how much the line traced by the worker was out with respect to the pre-marked traces. Weight factors were then assigned for type of error and row position. A Precision Index (PI) was calculated according to (1):

$$PI = \frac{1350 - \Sigma weight \cdot error}{1350} \% \qquad (1)$$

The Precision Index increased when the task was executed with the exoskeleton with respect to when executed without it, being PI = 600 and PI = 475 respectively.

The average score of the Borg scale in this task was 2.7 and 1.6 without and with the exoskeleton respectively.

In general, we can observe that in this task the presence of the exoskeleton was beneficial for the perceived fatigue, for the time execution and for the precision with which the assignment was performed.

## 4 Conclusions and Future Perspectives

Passive exoskeletons are taken into account for possible introduction as supporting devices in the industrial manufacturing environment. FCA has planned a testing campaign to define applicability, usability and implementation of exoskeletons in working tasks.

In this paper, the experimental activity on the first prototype of the passive exoskeleton developed by IUVO is presented. Sixteen workers from a FCA automotive plant participated in the tests. Qualitative and quantitative results show a positive effect of the exoskeleton for those activities that involve a posture with raised arms. Workers increased their endurance time when wearing the exoskeleton and also declared a lower perceived fatigue. Moreover, also execution precision increased when using the device.

In general feedbacks from the use of exoskeletons are positive [7, 8, 10, 13], but before a systematic employment in manufacturing environment more aspects have to be enquired. Comparing the results obtained by experimental activities carried out by various authors is not straightforward, since the test campaign and the exoskeleton solutions are different. However, some general remarks can be pointed out.

In all the experimental tests [7, 8, 10, 12, 13], users were allowed to familiarize with the exoskeleton only for short periods of time. This involves a not optimal use of the device, but it may also hold back discomfort that only longer periods of use might reveal. With a longer training and daily usage the workers can develop specific strategies that might results in better performance, but also unexpected biomechanical load in anatomical regions other than the one directly interested by the exoskeleton (i.e. upper limbs or trunk).

It is important that the participants are experienced workers [7, 8]. Tests conducted with non-experienced workers could be misleading, since they might not be skilled at manual works and/or have not developed personal strategies to minimise the effort to accomplish the task. In case of experienced workers, a lower gap of the results obtained with and without the exoskeleton can be expected. Moreover, the sample participants seldom reflect the average range of the working population for age and body weight and build.

From a biomechanical point of view, posture and kinematics changes with and without exoskeleton have to be monitored as well and in this case long-term observation is very important. In the present study, only qualitative visual inspection was considered, comparing postures without and with exoskeleton, and no evidence of changes in posture was found. Considering the industrial environment, a mo-cap system based on inertial sensors can be effectively used to quantitatively assess postures and kinematics. Related to the biomechanical strains, electromyography can be helpful, but in general, only the activities of superficial muscles can be analysed. Considering that there can be dynamic changes in human body regions not directly interested by the exoskeleton (e.g. thighs, pelvis), electromyography evaluation needs to consider a large number of muscles. Biomechanical models can be useful to estimate the overall biomechanical changes [17] and to suggest which are the body regions that have to be further examined.

Another important aspect is users' acceptance, which usually can be considered only if the test campaign is conducted with experienced workers. In fact, not only comfort has to be assured, but also psychological aspects, compatibility with the work environment and potential benefits in every day routine activity have to be considered.

Finally, laboratory tests are a necessary step to have a first evaluation of the potential pros and cons of exoskeleton-assisted work, but the following necessary step is the evaluation of the devices directly into the manufacturing environment. For this reason, FCA is planning a test campaign directly in the plant. Volunteer workers will wear an improved prototype of the exoskeleton while executing their standard tasks. Daily time of usage will progressively increase up to the full shift duration in the $5^{th}$ day. The campaign seeks for a holistic evaluation of the device considering long-term trials. It also investigate how the presence of other workers, equipment, limited spaces may interfere with the exoskeleton.

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