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Subjective Effects of Using a Passive Upper Limb Exoskeleton for Industrial Textile Workers

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Abstract: Industrial wool textile production exposes workers mainly to the biomechanical loading of the shoulder joint. In this work context, which is characterized by poor machine ergonomics, exposure to biomechanical risk factors, and variable work organization, exoskeletons could facilitate work processes or could be a valuable means to protect workers from overuse injuries. Field evaluation is essential to verify the suitability of specific devices and their acceptance by users. As part of a pilot study, we examined the short-term subjective effects of a passive Arm-Support Exoskeleton (ASE) on workers performing repetitive overhead tasks. In a textile factory, eight workers participated in the study, answering questionnaires after carrying out a work session with (ASE) and without an exoskeleton (FREE). Participants had been using the Paexo exoskeleton for 4.2 ± 5.8 months (min 0–max 12). Subjective evaluations were collected regarding the workload (NASA-TLX) and relief (Borg's CR10 scale) obtained from the use of the exoskeleton, satisfaction (Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST)), usability (System Usability Scale (SUS)), and opinions on the ergonomics of the device (Ergonomics questionnaire). Workers reported a high workload (NASA 7.2 ± 1.0) and assessed a 46% reduction in effort on the CR10 in ASE conditions compared to FREE. They expressed high satisfaction with most characteristics of the ASE (100% satisfied with durability and effectiveness), high level of usability (62% of scores above 80, out of a maximum score of 100), and ergonomics of the device (88 ± 12, out of a maximum score of 110). In addition to the objective effects (electromyography (EMG) reduction) already demonstrated in a previous publication, these qualitative results demonstrate a positive perception by textile workers regarding the effectiveness, usability, and suitability of the exoskeleton. The adoption of ASE in the textile industry appears beneficial in the short term, but the impact associated with individual variables and long-term effects remains to be explored.

Keywords: overhead work; arm-support exoskeleton; occupational exposure; usability; ergonomics; occupational medicine; workload management

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1. Introduction

The textile wool industry, which transforms raw materials into high-quality products, is organized in production departments with machinery consisting of double-sided lines typically arranged in long rows (over 25 m) with successive and dense working positions (over 70 positions per line front). This arrangement involves work characterized

by repetitive movements (i.e., passage of the woolen threads in special guides, knotting of the threads, restoration of broken threads during processing, etc.), awkward postures (overhead work), and the use of force (loading of bobbins at the top) [1,2]. All of these factors, together with organizational and psychosocial risk factors (such as job-related stress, imposed work pace, mental workload, etc.) (Table 1), can play a role in triggering the development of Work-related MusculoSkeletal Disorders (WMSDs) [3–9]. Notably, this sector has the highest incidence of upper limb disorders and shoulder WMSDs, being among the most prevalent [10].

Table 1. Characteristics of occupational exposure in the textile industry.

- Horizontal density and wide height development in the structuring of machinery (maximum height reaching point > 200 cm);
- Different compositions of the work shift, with prolonged or intermittent repetition of the same type of task, or with alternation of different tasks;
- Carrying out tasks alone/in a team of 2–4 workers;
- Rapid and highly repetitive work cycles (cycle duration < 15 s);
- Incongruous shoulder postures ($flexion > 80^{\circ}$);
- Handling of loads ($weights \geq 3$ kg) present in some tasks;
- Repeated application of manual force in different directions;
- Phases of static and dynamic engagement of the upper limb;
- Mental commitment (respect for sequences of technical actions, detection of the need for machine intervention, care, and responsibility for the integrity of materials);
- High demand for precision and manual coordination associated with repetitive activities;
- Exposure to acoustic and thermal discomfort;
- Work pace not strictly imposed by machines, with the possibility of individual adaptation within certain margins;
- Possibility of adopting the individually preferred working technique within certain margins.

WMSDs are impairments of bodily structures, such as muscles, joints, tendons, ligaments, nerves, cartilage, bones, and the localized blood circulation system, caused or aggravated primarily by work and by the effects of the surrounding working environment. At present, WMSDs are the most common work-related health problem in Europe [8].

In European industries, WMSDs are associated with a 50% rate of work absenteeism and are responsible for 60% of all reported cases of permanent disability [10], not to mention the high individual cost in terms of decreased quality of life [11]. The financial costs of WMSDs in Europe account for 2% of the gross domestic product of EU-15 [12].

European legislation for the protection of the safety and health of workers sets a minimum standard for preventive interventions following risk assessment, with priority given to avoiding risks, combating risks at source, adapting work to the individual, and adopting technological solutions.

The implementation of new devices such as exoskeletons, assistive systems which transfer mechanical energy to the human body, can contribute to optimized work ergonomics and thus reduce exposure risks prefiguring a highly promising strategy to combat WMSDs in the future [13–16].

In addition to assisting in load handling and repetitive tasks, exoskeletons also provide workers with a means of maintaining non-neutral working postures, thereby reducing muscle strain and fatigue in performing quasi-static tasks [17]. Moreover, exoskeletons also improve worker productivity and assist aging workers [18].

Especially for specific areas of the human body where muscular effort is more remarkable, such as the shoulder which is subjected to muscle and joint contact forces, passive occupational exoskeletons for the upper limbs Arm-Support Exoskeleton (ASE) have been developed to assist workers when performing repetitive or quasi-static tasks involving the upper limbs.

Exoskeletons' industrial use is, however, still limited and depends on a series of efficacy, safety, and acceptability-usability requirements verified in specific conditions [19]. Field studies are of great importance, allowing us to assess the subjective effects linked

to the use of the device and what factors influence their acceptance and habitual use [13]. Parameters such as discomfort, perception of fatigue, and perceived workload, but also effectiveness and usability or the perception of safety, could capture the "user experience" [14] and be used to assess the ergonomic adequacy of exoskeletons in real work situations, or prospectively to improve the design of certain models.

In this pilot study, we considered the subjective effects (perception of effort, satisfaction, usability, and ergonomics of the device) associated with the short-term use of an ASE by textile workers when performing repetitive tasks with the upper limbs on industrial textile machinery.

2. Methods

The study presented in this paper was conducted on workers in a wool company who were provided with an exoskeleton to support tasks with high physical demands. In this chapter, the materials and methods used are described in detail.

2.1. Exoskeleton

The passive exoskeleton tested in our experimentation is Paexo Shoulder (Figure 1) (Ottobock, Duderstadt, Germany), a very light (1.99 kg) and adaptable model, whose main purpose is to reduce the load on the upper limbs during overhead work. Passive exoskeletons do not use any actuators. Instead, they rely on elements such as springs and dampers to store and release energy generated by the user's movements to support a posture or motion at a specific joint.



(**a**)



(**b**)

Figure 1. The Ottobock Paexo Shoulder worn; a front (**a**) and back (**b**) view.

The Paexo device was shown (in a laboratory evaluation) to be effective in reducing shoulder muscle activity without negatively affecting trunk activity or performance,

eliciting positive user ratings [20–22]. To date, no field evaluations of Paexo have been conducted in real working conditions [14].

2.2. Participants

The study was conducted in a wool processing textile company located in Northern Italy as part of an ongoing experiment, where the employer, in the past year, provided a novel passive ASE for voluntary use by employees during specific work tasks. To each worker who adhered to this proposal, the employer assigned the same type of ASE that could be freely used during work, at the discretion of the worker.

Among the workers who had already experienced ASE, eight volunteers were recruited for this pilot study, at the suggestion of the Department Manager and the company's Safety Representative. The recruited subjects all had to hold the position of production worker and have good experience in spinning/winding lines. No anthropometric criteria were adopted in the selection of workers, as the small number of available subjects did not allow for this. The only exclusion criterion was the presence of acute disorders preventing the performance of repetitive work activities. Compliance with this criterion was managed using direct consultation with the worker and did not require the intervention of the occupational physician nor the consultation of occupational medical history.

In the selection, attention was paid to a fair distribution by gender and age in order to increase the representativeness of the sample in relation to the actual working population.

The research project received official approval from the Ethics Committee (approval number 2732 EC).

Each participant received detailed information about the research objectives and methods and voluntarily confirmed their participation in the study by written consent. Four men and four women participated in the study (Table 2). The average age of the subjects participating in the study was 40.7 $\pm$ 12.7 years old (min 20–max 55), and working seniority was 17.3 $\pm$ 15.4 years (min 7–max 39). All had right laterality and had been using the Paexo exoskeleton for 4.2 $\pm$ 5.8 months (min 0–max 12); in particular, three had been using the exoskeleton for more than 10 months ("experts"), while five workers had only been using the exoskeleton for a few days ("novices").

Table 2. Demographic characteristics of the study population.

	Age (yr)	Height (cm)	BMI	Exoskeleton Use (Months)
mean	40.8	172	23.1	4.29
std	12.7	7	2.9	5.87

2.3. Operational Session

The operational protocol consisted of two sessions for each participant, with (ASE) and without (FREE) the use of the exoskeleton. For each subsequently tested participant, the order of the ASE and FREE sessions was alternated to minimize possible biases due to the experimental condition. A break of at least 10 min was respected between the two sessions. During each session, the worker performed three repetitive tasks (A, B, C), all involving overhead work and with high biomechanical exposure as calculated according to the Rapid Upper Limb Assessment (RULA) method [23]. The RULA is a screening tool developed for use in ergonomic investigations of workplaces on tasks that involve biomechanical engagement of the upper limb. The evaluation of the biomechanical and postural load, particularly focused on the neck, trunk, and upper limbs, generates a score with a list of actions to reduce the risk of injury due to the physical load on the operator. Tasks were selected based on their relevance and recurrence in industrial textile activities, as well as based on the potential benefit brought by the ASE.

In Activity A, the worker is required to lift a bobbin (approximately 3–3.5 kg) from a service trolley with both hands and raise it to a height of 200 cm by applying pressure to fix it onto a pin. The objective of Task B is to operate the spinning machine, which has

been loaded with five pairs of spools (anterior and posterior row). The worker is required to take a couple of threads, slip them with both hands from a spool, and insert them into the lower parts of the machine. In Task C, the worker is required to transfer a set of dozen tubes (each weighing less than 0.1 kg) from a trolley to the top of a twisting machine at a height of 210 cm.

The three tasks were performed under real conditions on respective machines, interspersed with rest periods, and each task continued for a duration sufficient to complete a predetermined number of cycle repetitions. During the operational sessions, the pace of execution of the activities was not fixed, and the worker was free to adopt his/her usual work pace and preferred technique. The operational session aimed to test workers' experience of the two conditions, ASE and FREE, while carrying out biomechanically relevant work tasks. The study focused on the subjective perceptions associated with each condition.

Following the completion of the operational sessions, lasting approximately 1.5 h in total, each worker was asked to complete multiple questionnaires relating to the perception of the workload and their experience with the exoskeleton.

2.4. Subjective Evaluation Session

After the operational sessions, each worker was required to complete the subjective evaluation by filling out the questionnaires in the following order, as introduced and briefly explained by the experimenter:

- NASA-TLX (NASA-Task Load Index, simplified version) [24]. This multi-dimensional rating scale was applied to assess the subjective workload perceived by the worker, referring to the textile working operations performed without an ASE. The estimate of the workload is obtained by combining the magnitude of six workload-related factors (mental demand, physical demand, temporal pressure, physical effort, frustration, and satisfaction of performance), evaluated on a visual analog scale equated to an extended range between 0 and 10. According to studies previously carried out with the NASA-TLX tool, the ratings provided through the index correlate with other factors that are relevant to performance (i.e., teamwork, fatigue, stress, age, personality, experience). The magnitude of the workload detected through NASA could be useful for identifying the opportunity to adopt ASE as a support in carrying out work tasks where there is a risk of overload.
- Borg's CR10 scale [25]. This category ratio scale (numerical range between 0 and 10, from low to maximal level of effort) is used to evaluate the perception of physical effort about a performed task. In this study, we applied the scale to obtain a comparison of the subjective effort perceived while carrying out work in the condition without (FREE) and with (ASE) the exoskeleton. In particular, the worker responded to the question "what level of physical effort do you perceive when you work, if you use/don't use the exoskeleton?" by attributing a value (between 0 and 10) to the effort perceived in each working condition.
- Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) [26]. This is a tool for evaluating the satisfaction of the user with the adoption of assistive technology, with particular reference to eight device characteristics (i.e., size, weight, adjustability, safety, durability, ease of use, comfort, effectiveness) and four aspects of the service delivery. Scores are assigned to each item on a Likert scale from 1 (not at all satisfied) to 5 (very satisfied), and the total score is obtained from the average value of the ratings assigned by the participant (i.e., Product Satisfaction Score: <sum of the scores of items 1 to 8 > divided by 8). Workers' satisfaction with the features of the ASE could influence their readiness to actually use it.
- System Usability Scale (SUS) [27] (Table 3). This tool measures the usability of technology. Ten constructs connected to the conditions and advantages of use (for example "I think I'll use ASE frequently") are evaluated on a Likert scale from 1 (not at all agree) to 5 (fully agree). The overall SUS score (range 0–100) calculated according

to an algorithm [28] represents a composite measure of the overall usability of the system studied.

- The Ergonomics questionnaire (Table 4) was developed specifically by an author of this group for this pilot study, particularly focused on issues of safety and health at work [29,30]. The items refer to ergonomic aspects (i.e., effectiveness, versatility, dimensions and adaptation to anthropometry, and expectations). Both technical (related to improved productivity or tolerability of the assigned task) and safety expectations (prevention of WMSDs and compatibility with personal protective devices) were explored. Acceptance and social liking of the device were also included. An algorithm similar to that of SUS [28] was applied to calculate the final score (range between 0 and 110, with eleven items rated). The first and last items of the questionnaire did not enter into the final calculation, but they were used to deepen issues related to the opportunity to use ASE, already detected by the previous questionnaires (i.e., "workload" in NASA and "safety" in QUEST).

Table 3. SUS Usability Questionnaire items, referring to the exoskeleton.

No.	Statement
1	I think I will use this exoskeleton frequently.
2	This exoskeleton seems too complex.
3	I think I will find this exoskeleton easy in use.
4	I think I will need assistance in use this exoskeleton.
5	I find the various functions very well integrated.
6	I find a lot of inconsistency in the functions offered.
7	I imagine that most workers can quickly become accustomed to the use of the exoskeleton.
8	I find this exoskeleton to be very cumbersome and uncomfortable.
9	I feel very comfortable using this exoskeleton.
10	I had to learn many things before I could use this exoskeleton easily.

Table 4. Items of the Ergonomics Questionnaire.

No.	Statement
1	My work is physically demanding
2	Exoskeleton can improve worker productivity
3	Exoskeleton can reduce musculoskeletal disorders
4	Exoskeleton can reduce the need to be assigned to alternative tasks
5	The exoskeleton is effective
6	The exoskeleton is versatile
7	Exoskeleton promotes worker responsibility
8	The exoskeleton is robust and durable
9	The exoskeleton is appreciated by most of us
10	The weight, the size is appropriate
11	Fits well with anthropometry
12	Interfaces well with other personal protective equipment
13	The exoskeleton presents security problems

We chose to collect workers' opinions immediately after carrying out an operational session, which involved carrying out real work tasks with overhead work, in conditions with (ASE) or without (FREE) the exoskeleton.

The study followed the literature's indications for recruiting the sample, limiting it to those employed in the sector and ensuring a balance between males and females. The questionnaires were administered in a specific order, starting with the evaluation of the workload and followed by the evaluation of the exoskeleton's characteristics [14]. This helped to minimize the potential for nocebo-placebo effects (associated with the presence of exoskeletons during the experimentation) and discrepancies in perception between genders (associated with different dimensions and corporeality conformations) that could significantly influence the user experience.

2.5. Statistical Analysis

Descriptive statistics, including mean and standard deviation of scores and frequency distribution, were used to evaluate the results obtained from the questionnaires.

All statistical analyses were performed using Jamovi software (Jamovi Project, Sydney, Australia).

3. Results

3.1. Biomechanical Load of the Tasks Performed, Estimated by RULA

The final RULA Score (whole body score), is a single score that represents the level of WMSDs risk for the job task being evaluated, based on posture, load/force applied, and duration. The final score is derived from a combination of evaluations attributed to the upper and lower arm, wrist, neck, trunk, and leg sectors. The minimum RULA Whole Body Score is 1, and the maximum is 7, which indicates a very high risk with an urgent need for ergonomic modifications to reduce the risk of the task. According to the evaluation of the RULA method, all three tasks A, B, and C performed by the workers in the operational session involved a significant biomechanical load (Table 5). Intervention recommendations associated with RULA scores of 5–6 concern "further investigation, intervene as a priority", while for scores ≥ 7 they concern "investigate and implement urgent changes".

Table 5. Characteristics of the tasks performed during the operational session.

	Task A	Task B	Task C
Cycle Duration (s)	4	10	2
Cycle Content	one bobbin attached at a height on the machine	two threads ducts and inserted into the processing passages of the machine	one tube placed at the top of the machine
Technical Actions/min Left	30	36	30
Technical Actions/min Right	45	42	60
Shoulder Flexion $> 80°$ Dominant Side (%)	25	55	80
Applied Force/Load per Cycle (kg)	3.5	2	-
RULA Whole Body Score	7	5	7

3.2. Subjective Perceptions of Workload and Load Reduction Achieved Using the Exoskeleton

The perception of the workload associated with the textile industrial activity, assessed using NASA-TLX, is in the medium–high range (7.2 ± 1.0) for the sources associated with mental and physical load, time pressure, and effort (Table 6). On the Borg's CR10 scale, the average value of effort in the FREE condition is 5.2 ± 0.9 (with 5 equal to "heavy effort"), while with the exoskeleton (ASE), the perception of effort is on average 2.7 ± 0.4 (with 3 equal to "moderate effort") (Figure 2). This corresponds to an average effort reduction of 46% in the ASE condition compared to FREE.

Table 6. NASA-TLX scores referring to main sources of workload.

Mental Demand	Physical Demand	Temporal Demand	Effort	Average NASA-Score
7.3	6.9	7.4	7.2	7.2 ± 1.0

For all workers, the ASE condition involves reduced levels of effort compared to the FREE condition. For two subjects (#5 and #8), the difference in FREE–ASE score takes a value of four units (from 6 to 2, and from 7 to 3 on the Borg's scale), while for all other subjects, a constant decrease of two units is observed. The perception of effort and the development of fatigue, which are complex and interrelated phenomena, affect the tolerance to the task and the sustainability of the worker's performance, impacting on final productivity.

In particular, fatigue develops when the worker perceives that the effort to complete the task is greater than expected.

The possibility of intervening effectively, for example, through the use of ASEs, to reduce the impact of fatigue and increase tolerability, improving performance, is a possibility that deserves to be further explored for the important practical effects for safety and economy in the workplace [31].

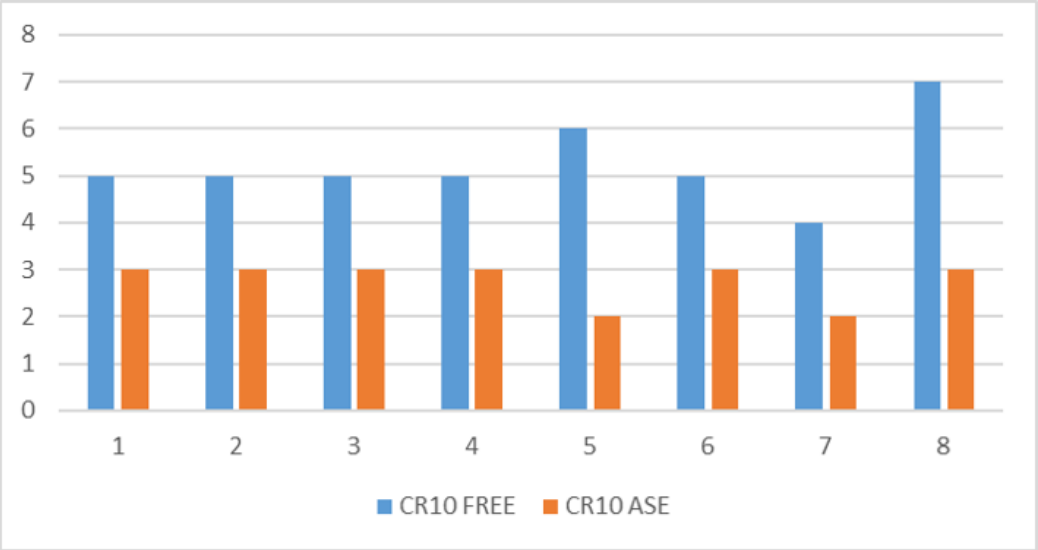


Figure 2. CR10 evaluations of the eight workers with respect to FREE and ASE work condition.

3.3. Satisfaction, Usability, and Ergonomics of the Exoskeleton

User satisfaction, usability, and device suitability with respect to the work context were investigated using the QUEST, the SUS, and the ad hoc Ergonomic Questionnaire, respectively.

The overall QUEST scores, rated by participants on a Likert scale (from 1 "not at all satisfied" to 5 "very satisfied"), were divided into two groups to identify a level of low satisfaction (scores 1 to 3) and a level of high satisfaction (scores 4 to 5). This categorization enabled a clear distinction of participants' satisfaction levels with the ASE (Figure 3). We focused our attention on the items relating to the characteristics of the device (QUEST–device). Overall, 100% of participants were completely satisfied with the durability (mean 4.37; std $\pm$ 0.52) and effectiveness (mean 4.75; std $\pm$ 0.46). The weight (mean 4; std $\pm$ 0.93) and safety (mean 4.12; std $\pm$ 0.64) of the device were fully satisfactory for 87.5% of the participants, while ease of use (mean 4.25; std $\pm$ 1.16) and comfort (mean 3.62; std $\pm$ 0.74) were satisfactory for 75% of the workers.

The lowest levels of satisfaction were observed for adjustability (mean 3.5; std $\pm$ 0.93) and dimensions (mean 3.5; std $\pm$ 0.53). Satisfaction with the supply service reached full agreement for 87.5% of workers.

The highest SUS score was 97.5 (out of a maximum score of 100), and the lowest was 57.5 (average of 79.06, std $\pm$ 14.45). In percentile terms, 87.5 is at the 75th percentile, 82.5 at the 50th percentile, and 66.9 at the 25th percentile. The exoskeleton received predominantly excellent perceived usability, with 62% of participants scoring above 80. The detailed analysis of the single items identifies the following aspects as those considered most satisfactory by users: integration of functions, ease of use, comfort, ability to get used to the device, and intention to use. Critical aspects include need for assistance, excessive complexity, bulkiness, and need for training.



Figure 3. Satisfaction responses in relation to the delivery service (top) and in relation to the ASE (bottom). The abscissa shows the percentage of subjects declaring themselves to be slightly (in blue) and very satisfied (in orange), respectively.

The ergonomics of the device assessed through the ad hoc Ergonomics questionnaire received a medium–high overall rating (mean 88 ± 12, out of a maximum value of 110) (Figure 4).

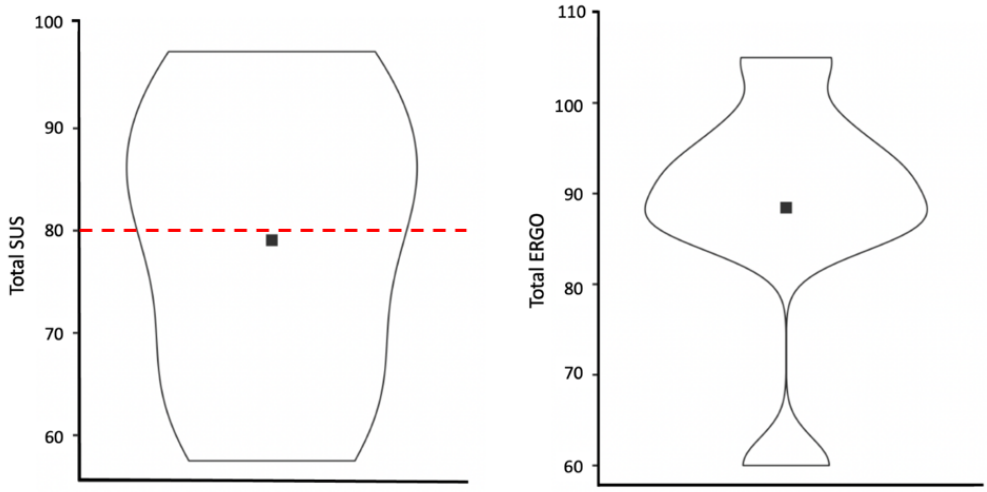


Figure 4. Distribution of scores obtained from the SUS and Ergonomics questionnaires, shown in violin graphs with an indication of the average value. The width of the curve corresponds with the approximate frequency of data points in each region.

The constructs that concordantly received a positive rating (scores ≥ 4) were, in ascending order, as follows: the exoskeleton is appropriately sized, promotes empowerment, fits the worker's anthropometry, is robust, can be interfaced with personal protective equipment, promotes productivity, is effective, and reduces the occurrence of WMSDs. This last item (exoskeleton can reduce WMSDs) received the highest score.

Among the critical aspects, two workers expressed concerns about safety, hypothesizing problems with the bulk of the exoskeleton used between the machinery aisles.

3.4. On-Site Observation

Field observations of all phases related to the use of the exoskeleton by workers provided us with the cue for some considerations on the practical aspects of donning/doffing the device:

- An "experienced" worker takes about 60 s to don the exoskeleton and about 30 s to remove it; an "inexperienced" worker takes about three times longer, often requiring assistance.
- Attaching the exoskeleton to the body, before it can be used, requires the worker to perform a precise sequence of manual actions (grasping, positioning, and closing hooks and straps) that are not always intuitive to the worker.

4. Discussion

In this field study, we explored, for the first time in the industrial wool textile manufacturing sector, the short-term effects of using a passive exoskeleton for the upper limbs during repetitive tasks involving overhead work. The quantitative results relating to the instrumental measures (electromyography (EMG)) taken during the described experimental sessions have already been reported in [32]. Here, the qualitative results regarding workers' perceptions associated with the use of ASE in the short term are exposed. The study participants were volunteers who were part of a group in the textile company participating in an ongoing experiment. The employer provided a new passive ASE (Ottobock Paexo Shoulder) for voluntary use by employees during specific working tasks. The sample of workers analyzed was limited; however, we ensured gender and age balance to represent the general working population. This approach aligns with the recommendations for field trials of exoskeletons [14].

The study participants used the exoskeleton for a relatively short period of time, with an average of 4.2 ± 5.8 months (minimum 0–maximum 12). Among them, three operators were considered "experts" as they had been using the exoskeleton for more than 10 months, while five operators were considered "novices" as they had only been using it for a few days.

High workloads are present in the textile activity considered (NASA mean score for the main sources of workload 7.2 ± 1.0) (Table 6), an opinion also confirmed by the answer provided to the first item of the Ergonomics questionnaire.

The three considered working tasks, typically performed in the Spinning and Winding processes where the prevalence of shoulder symptoms reported by workers is highest [1], showed high RULA scores for the biomechanical exposure, and the indication of improvement intervention is compelling.

According to the literature, arm elevation and shoulder load double the risk of specific soft tissue shoulder disorders [5], but the impact of factors related to the shoulder WMSDs may differ in each specific work area [33]. The work tasks considered in our study implied shoulder flexion >80° for the dominant side for 25–80% of the work cycle (Table 5), as well as application of force and demand for precision.

Exoskeletons can represent technical devices that support workers in performing demanding job tasks. Potentially, they are applicable to all workers, especially in those work contexts where structural solutions may be difficult to implement due to structural constraints, such as in the textile sector. The use of Paexo in the textile context reduces muscle activity in the anterior and medial deltoid (21–13% reduction), without resulting in increased activity of the trunk muscle [32]. In the same study, the biomechanical effect of Paexo is independent of the task's risk level, the time of use of the device, and the subject's Body Mass Index (BMI). Questionnaires submitted to the workers participating in the same pilot study enabled the precise capture of their perceptions regarding the effectiveness of the exoskeleton, beyond what was demonstrated instrumentally.

When introducing new technologies like exoskeletons into the workplace, it is crucial to consider user acceptability. This is primarily determined by perceived ease of use, effectiveness, and absence of discomfort [34].

Furthermore, the specific effects of the exoskeleton in real working conditions should provide workers with the perception of obtaining adequate and beneficial support for work performance [35]. This perception of advantage would also represent an important factor in counteracting the development of disabilities resulting from musculoskeletal disorders [36,37]. Therefore, exoskeletons that reduce the workload when performing high-risk biomechanical tasks are likely to be better accepted by workers and foster perceptions of benefit.

In our sample, textile workers expressed full satisfaction regarding the durability and effectiveness of the ASE (average scores of 4.4 and 4.7, respectively, on the QUEST) (Figure 3), representing a favorable prerequisite for the habitual adoption of the device in this working environment. The weight of the ASE (1.99 kg), which fully satisfies 87% of the sample, is equivalent to 3–4% of the body weight of the subjects, and well below the recommended limit for school backpacks [38]. The device is lightweight, easy to use, wear-resistant, and relieves effort, which lays the foundations for widespread and habitual use [39].

Workers' limited satisfaction with size and adjustability aspects (average score of 3.5 in the QUEST) could be due to the fact that the individual fitting of the device provided at the time of initial assignment to each worker was not re–verified afterwards, e.g., to correct strapping pressure, or to readjust the device based on individual body morphology.

Despite this, the ease of use and comfort fully satisfied 75% of the sample (QUEST) (Figure 3) and received a high SUS score (4.3 and 4.1, respectively), indicating that the type of ASE was overall perceived by the workers as suitable and functional with respect to the occupational context (a high SUS score, 4.5, was also attributed to a good integration of functions). Workers also believed that it is possible for everyone to quickly get used to using the ASE (SUS score 4), and all but one thought they would use it frequently (SUS score 3.75).

End users' attitudes and usage intentions are influenced by their perceived comfort and compatibility with the technology [40]. Intention to use exoskeletons could decrease over time due to factors such as discomfort, perception of insufficient support or inadequacy, and work context [41]. Some authors have reported that female users experience discomfort related to the use of exoskeletons [14], linked to continuous use and localized pressure [42–44], as well as to sensations of heat or discomfort [35,45], or limited versatility of the device [46]. The physical interaction between man and exoskeletons deserves to be studied not only through the detection of subjective discomfort data, but also through precise metrics and technologies. For example, the analysis of the temporal effect of contact pressures through sensors or optical instruments could provide fundamental indications about the comfort and tolerability over time, and safety of devices [47]. Especially in the textile industry, where the work environment is characterized by high humidity and heat, and where the wide range of motion of the upper limb could over time cause human–exoskeleton joint misalignments, it is important to detect any discrepancies in the interaction with the exoskeleton that could reduce its acceptability or compromise its safety.

In our study, the inclusion limited to volunteers could have lead to selection bias, as participants may differ systematically from the general population. Volunteers can potentially possess specific traits such as heightened interest, better health, or greater availability, leading to non-representative samples and reduced generalizability of results. To mitigate this bias in future studies, employing random sampling techniques selection is crucial. Moreover, future research that includes numerically ample samples balanced by gender, but also by age, state of health, and type of occupation, could provide a holistic view helping to better understand exoskeletons' applicability in the industry. From an ergonomic point of view, considering the effects of the exoskeleton associated with different anthropometric dimensions (in particular at the 5th and the 95th percentile, for a broad representativeness of the sample) would contribute to inclusive design. In our pilot study, we did not analyze the results broken down by gender, as we felt we could not foresee any interesting results in this respect, due to both the small size of the sample and the absence of

an anthropometric selection criterion. However, this appears to be of the utmost relevance in the textile context, where majority of employees are female, usually characterized by a smaller body stature and lower strength capacity than the male gender.

In our study, recruitment of an equal number of male and female workers to include in the sample, responds to a critical issue often overlooked in many studies [48], and resulting in strong gender unbalance in the test populations [49].

Detecting the factors that influence the acceptance of exoskeletons in specific industrial contexts can be useful for setting up new designs or redesigning or evaluating new or existing exoskeletons. This approach can enhance the quality of exoskeletons by allowing designers to include acceptance factors early in the design process and encourage a faster adoption of exoskeletons in the workplace [39].

Highlighting the characteristics that optimize the match between exoskeleton, specific activity, and user [50] can maximize the beneficial effects and minimize unwanted results [51]. In the textile sector, specific work requirements such as the demand for precision combined with the handling of loads have important physiological and biomechanical effects on workers and can influence task performance [45]. Negative effects possibly associated with the limitation of joint movements or the modification of the working technique imposed by the ASE may have negative effects on the acceptance of the devices or the perception of their advantages in the long term [17]. In the case of Paexo, the footprint of the exoskeleton is light and relatively small as it adheres directly to the body and should not, in theory, hinder any movements of the limbs or trunk. Significant deviations from natural motor patterns due to ASE could reduce the degree of user acceptance [21,52] or impair worker performance, preventing the achievement of quality requirements characteristic of woolen textile products.

The use of exoskeletons in the context of textile production necessitates an in-depth analysis, encompassing the verification of usability, comfort, and ergonomics alongside the parameters of performance. It is evident that the use of exoskeletons, due to physical encumbrance or mechanical constraints, could potentially alter the kinematics, speed, or agility of technical working movements in this type of work activity, which is characterized by the demand for a high precision and high quality of the final product. This could consequently impact the quality of the final product or result in greater frustration for the worker.

The effects on performance, which may be observed in terms of the duration of execution and completion of work tasks, the absence of technical errors in the conduct of work sequences, and the satisfaction of expected quality requirements on the end product, help to define the economic sustainability of preventive interventions aimed at improving work ergonomics. These effects could, therefore, be used as objective parameters in a cost–benefit analysis to promote the introduction of this technology in industrial settings [53].

Safety concerns (last open question of the Ergonomic questionnaire, Table 4) emerged from the assessments of two workers, related to the overall volume of the rear joints of the exoskeleton, and the possible collision with machinery and equipment located in the surrounding work areas. Actually, the rear joints of the exoskeleton protrude about 10 cm above the shoulder in the rest position, while during the active phases, they remain within shoulder height (Figure 5). In order to respond to these concerns and increase the level of perceived safety, we proceeded together with the Safety Manager and the workers to verify the real conditions of use of ASE. First of all, we verified that the rear bulk of the ASE in the active phase did not interfere with the surrounding structures in the work area. Then, we formalized the safe ASE use method within each department, so as to avoid the risk of accidental collision with other structures or machinery in any work area. This input also promoted the company's initiative to set up a prolonged training program with ASE in order to more comprehensively understand possible obstacles to its use [52,54,55] or identify new emerging risks and better respond to these issues.



Figure 5. A study participant performing a spinning task while wearing Paexo.

Direct observations of the use of ASE in the field revealed some critical issues during the don/doff phases, which could be resolved through a more user-centered design, making it easier and more agile also for intermittent use during the workday [56].

In fact, although the biomechanical advantage of ASE extends to different types of conditions [32], not all tasks carried out in the textile industry benefit from the use of ASE, and the worker could choose to use it only for some specific tasks characterized by repetitive gestures, incongruous postures, and handling of light loads. In our study, the "experienced" workers found benefit in using ASE for approximately 2 h per day, especially for carrying out task A.

Regarding the potential of exoskeletons to reduce the risk of WMSDs, it is interesting to note that in our sample the workers assigned to this item the highest score in the Ergonomics questionnaire. This perception is in line with the biomechanical results obtained previously on the same sample analyzed [32], where the effectiveness of ASE on muscle activity was even independent of the type of task performed.

The use of Paexo in the textile sector could benefit workers by increasing their activity tolerance and delaying the onset of fatigue over the course of the shift. However, our study was limited to a short observational period, and it is not possible to draw any conclusions regarding the long-term effects of using Paexo, including its impact on the development of WMSDs.

Apart from preventative purposes, the adoption of exoskeletons in industry appears to be influenced by their impacts on quality and productivity, as well as by economic implications [53]. Therefore, the adoption of exoskeletons should also be evaluated by quantifying the benefits of keeping older or disabled workers active, supporting their performance at satisfactory levels, and minimizing the risk of long-term disability [52].

What appears from the recent literature is that exoskeletons can be considered a technical solution to lighten the workload and streamline work processes during repetitive and overhead work, but a comprehensive assessment of their fit, usability, and effectiveness needs to consider both different working conditions (postures, tasks, organization) and users [17,57–60]. In this regard, field studies, even if they involve a greater effort for both workers and researchers, are essential and should be strengthened to examine the physiological, performance and subjective aspects associated with exoskeletons, without neglecting to consider the impact on the qualitative and economic aspects of production. Ergonomic considerations in the use of exoskeletons are essential to guarantee the well-being of the worker and can contribute to the creation of more sophisticated and comfortable exoskeleton models, better suited to individual movement and dimensions. Furthermore, standardized ergonomic risk assessment methods will need to be developed in the future, which take

into account the alleviation of biomechanical burden due to the use of exoskeletons by workers [61].

5. Conclusions

Our study examined the subjective effects associated with ASE use during short work phases carried out on industrial machines for the processing of wool, characterized by repetitive engagement of the upper limbs, overhead work, and light force engagement.

By testing a small sample of workers in the sector, we obtained results that suggest subjective benefits from the use of passive ASE and, combined with previously demonstrated biomechanical benefits, would seem to support a wider implementation of this technology in the industrial textile sector, in order to improve ergonomic working conditions and the well-being of workers.

Even if the limitations of the study do not allow us to draw solid or generalizable conclusions, it is important to continue the experimentation of exoskeletons in real working conditions and with workers in the sector, expanding the case series and including genders, anthropometries, and job positions in a fair and representative way. In addition, an effort by researchers towards a multidisciplinary and technological approach to the study of the effects associated with the use of exoskeletons would allow us to deepen the level of quality of the studies and increase the value of the parameters detected, through the integration of subjective, instrumental, and economic and health-related data. This would make it possible both to identify valid criteria to discriminate the opportunity to use exoskeletons in different work environments and to appreciate their actual advantage in terms of health, safety, and productivity.

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Abbreviations

The following abbreviations are used in this manuscript:

ASE	Arm-Support Exoskeleton
BMI	Body Mass Index
EMG	Electromyography
EXO	Exoskeleton
QUEST	Quebec User Evaluation of Satisfaction with Assistive Technology
RULA	Rapid Upper Limb Assessment
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SUS	System Usability Scale
WMSD	Work-related MusculoSkeletal Disorder

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