Effect of passive exoskeleton to assist upper limbs during overhead work tasks

Mathis CHESNEAU[a], Thomas ALBOUY[a], Kévin LEBEL[a]. Bérenger LE TELLIER[a]*

[a]ErgoSanté – 28 ZA de Labahou, Anduze, France

* b.letellier@ergosante.fr

Abstract

Musculoskeletal disorders of the upper limb are a significant concern in terms of occupational health. Prevention has become a major issue for companies, which are progressively turning to physical assistance devices such as exoskeletons. Thus, the present study aimed to objectively evaluate a new passive exoskeleton (muscle activity, limb kinematics, and center of pressure displacement) and subjectively assess perceived discomfort. Thirteen volunteers were required to perform two tasks representative of professional activities: an overhead tool-holding task and a vertical handling task, both with and without the exoskeleton. The results showed a reduction of approximately respectively 40% and 30% in the activity of the anterior deltoid muscle, respectively. Besides altering user kinematics, the exoskeleton did not disrupt postural balance nor lead to overactivation of antagonist muscles during movement. The study results confirm the strong potential of this exoskeleton in reducing one of the risk factors for musculoskeletal disorders of the shoulder.

Key-*words: UL-MSDs, Shoulder pain, Passive exoskeleton, EMG, Postural balance, Kinematics, Perceived discomfort*

1. Introduction

Musculoskeletal disorders (MSDs) are a major public health problem, affecting nearly 40 million workers in the European Union according to Eurostat (2010) [1]. In France, MSDs are the leading cause of recognized occupational diseases under the general scheme, accounting for 87% of cases in 2021 [2]. This joint structure is particularly vulnerable to conditions classified as upper limb MSDs (UL-MSDs), which involve inflammatory and degenerative lesions of the upper limb. They typically affect tendons, muscles, joints, nerves, and vascular elements, leading to stiffness, loss of strength [4], and characterized by painful symptoms. Similar to low back pain [5], UL-MSDs can become chronic conditions and may even become irreversible, resulting in lasting disability if not adequately addressed early on [4].

While the onset of UL-MSDs is multifactorial [6], it commonly involves biomechanical overloading in the majority of cases [4]. Despite the current trend towards automation in the industry and prevention efforts, many workers are still exposed to significant physical constraints. Scientific literature has established strong links between the occurrence of shoulder MSDs and exposure to repetitive tasks [7], [8], as well as continuous exposure to static or constrained postures [7], [9]. Particularly, overhead work has been directly associated with the development of UL-MSDs [7] [8]. Furthermore, the cumulative and maximum discomfort perceived during work appears to be a predictor of long-term MSD development [5], considering that the effects of work-related physical exposure may persist even after the end of one's professional life [8].

MSDs have significant economic and social consequences, ranging from absenteeism and costs for employers and the healthcare system to difficulties for workers in performing their daily tasks. This underscores the need to improve prevention efforts. Limiting risk factors becomes one of the main challenges in the fight against UL-MSDs [10]. With a focus on the development of ergonomic workstations, prevention efforts also involve the use of Physical Assistance Devices (PADs) such as exoskeletons. Numerous scientific studies have demonstrated that exoskeletons can lead to reductions of 32% to 62% in the activity of the anterior arm muscles during repetitive and static overhead activities [11]–[15]. Despite their beneficial effects for workers, the scientific literature has shown that these technologies can lead to discomfort, involuntary activation of antagonist or stabilizing muscles [16], perceptual disturbances that may impact balance [14], [16], [17], and, in some cases, affect the user's kinematics [18].

The objective of the present study is to evaluate the passive exoskeleton HAPO UP (ErgoSanté, France) for overhead work tasks. This evaluation is based on objective criteria, including myoelectric activity, center of pressure displacement velocity, and kinematics, as well as subjective criteria related to perceived discomfort.

2. Method

2.1. Participants

Thirteen adult volunteers participated in this study, including 3 females (31 ± 7 years old, 160.7 ± 3.1 cm, 59 ± 2 kg) and 10 males (24.1 ± 4 years old, 178.5 ± 5.1 cm, 73 ± 9 kg), with no history of neuromuscular disorders in the upper limbs. Informed consent, both written and verbal, was obtained from all participants prior to their inclusion in the study. They were recruited from among voluntary workers at ErgoSanté who were not involved in the design of the exoskeletons. Participants were asked to refrain from engaging in intense activities for at least two days prior to the experiment to avoid the risk of neuromuscular fatigue.

2.2. Physical Assistance Device

The HAPO UP exoskeleton is a passive assistive technology based on the principle of energy storage and release using a composite material spring blade located at the shoulder level. This composite blade provides optimal assistance to the arm during the 60° to 180° range of elevation. Weighing 1.67 kg and featuring a single adjustable size, the PAD offers a variable level of assistance ranging from 1.6 to 3.8 kg per arm (equivalent 4 to 9 N.m). A passive disengagement mechanism inhibits the PAD assistance when the arms are in a low position (<60°).

The device consists of an adjustable belt to which two carbon masts are connected through ball joints, and their positions on the belt as well as their lengths are adjustable. The articulation between the mast and the boom is ensured at the shoulder level by a pivot connection, assisted by the composite blade. The boom is connected to a textile interface in which the user's arm is positioned.

The mechanical action of the exoskeleton aims to support the user's arm by transferring a portion of the weight applied on the arm to the user's pelvis.

Figure 1: Exoskeleton HAPO UP, ErgoSanté, France. (1) Belt; (2) Mast; (3) Boom; (4) Interface; (5) Textile harness.

2.3.Process

After joint and muscle warm-up, participants were instructed to perform two tasks under two conditions: with and without the exoskeleton. The order of conditions ("with exo" and "without exo") was systematically varied from one subject to another. The exoskeleton was individually adjusted to each participant's morphology through its various settings. The level of assistance was adjusted so that the weight of the arm was almost entirely compensated by the exoskeleton when both the shoulder and elbow were flexed at 90°. The setting was considered optimal when, after the user's muscles were relaxed, the arm naturally descended towards the pelvis.

2.3.1. Task 1: Holding a power drill above the head

Subjects were instructed hold a 1.26 kg power drill above the head with the right arm for a period of 30 seconds while standing on the force platform. Participants were instructed to maintain the elbow at the height of their nose level. The target angle between the trunk and arm (epicondyle, acromion, greater trochanter) was 110°.

Figure 2: Task 1: Holding a power drill above the head

2.3.2. Task 2: Load handling in vertical plane

Participants stood on the force platform facing a table adjusted to the height of their greater trochanter. A total of 16 kg, distributed in 4 equivalent stacks (1 x 2 kg + 2 x 1 kg) were aligned at the edge of the table. In addition, this task also required the use of a shelf previously set at a height corresponding to the participant's head top. Participants had to transfer all loads one by one from the table to the shelf, starting with the stack furthest to the left. The task was performed with the right hand. At the end of the task, participants placed in a standing position with their arms at their sides.

Figure 3: Task 2: Load handling in the vertical plane

2.4. Data acquisition and analysis

2.4.1. *Surface electromyography*

The electromyographic activity (EMG) of the anterior deltoid, biceps brachii, triceps brachii, clavicular portion of the pectoralis major, latissimus dorsi, longissimus, and upper trapezius muscles (Figure 4) was recorded only on the right side during the two tasks. Quadripolar surface electrodes (Trigno Avanti, Delsys Inc., Natick, MA, USA) were placed on the skin after prior preparation (shaving and alcohol abrasion) following SENIAM recommendations [19]. Before the experimental tasks, a maximum voluntary isometric contraction (MVC), performed against manual resistance provided by the experimenter, was sequentially conducted for all muscles. All contractions were held for 5 seconds and separated by at least 45 seconds of rest. The EMG signals were recorded at a sampling frequency of 2148 Hz.

Data processing was performed using Matlab® software (The MathWorks Inc., Natrick, MA, USA). The raw data were first rectified and then filtered using a fourth-order band-pass digital filter (20-450 Hz, Butterworth). Subsequently, the envelope of the signal was extracted using a 10 Hz low-pass filter (fourth-order Butterworth). For each muscle, a sliding window of 100 ms was used to determine the rectified and maximum mean value of each contraction. This value was then considered the reference value for each subject. Finally, for both tasks, the root mean square (RMS) average value was calculated for each subject, under both conditions. This value was normalized with respect to the corresponding reference value (MVC). The normalized values of the subjects were then averaged for each condition.

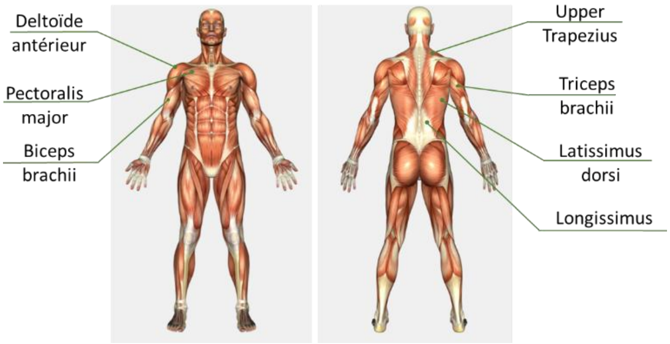


Figure 4: EMG electrodes placement on muscles.

2.4.2. *Inertial units*

Kinematic analysis was performed using XSENS software (MVN, Xsens Technologies, Enschede, The Netherlands). Inertial units were placed on the entire body, with 17 sensors positioned on the subjects. Data were recorded at 120 Hz. The average joint angles per subject were then compared between the two conditions. The focus was on examining the effect of the exoskeleton on the shoulder, elbow, and spinal joint angles.

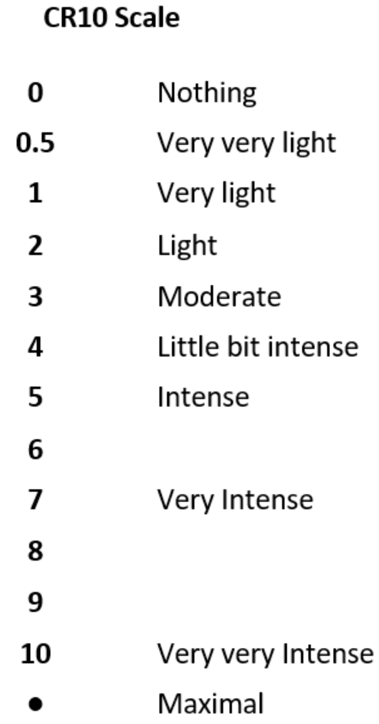
2.4.3. *Force plate*

The analysis of the center of pressure (CoP) was performed using an AMTI® force platform

(Advanced Mechanical Technology Inc, Watertown, MA, USA). The data was acquired at sampling frequency at 120 Hz and was filtered using a fourth-order Butterworth low-pass filter with a cut off frequency of 5 Hz. The CoP parameter was evaluated using the mean velocity (CoP_V) of the center of pressure.

2.4.4. Subjective scale

A categorical rating scale (CR10) (Figure 5) was used to assess overall perceived discomfort, in which participants were asked to consider all environmental factors, the task performed, and the use of the exoskeleton in their estimation. Participants were required to rate discomfort after each task.



CR10 Scale

0	Nothing
0.5	Very very light
1	Very light
2	Light
3	Moderate
4	Little bit intense
5	Intense
6	
7	Very Intense
8	
9	
10	Very very Intense
●	Maximal

Figure 5: CR10 scale.

2.4.5. Statistics

The conditions with and without the exoskeleton were statistically compared using a paired sample t-test with JASP software (0.17.1.0) (University of Amsterdam, Netherlands). Given the relatively small sample size (N = 13), the normality assumption was assessed for each sample using the Shapiro-Wilk test. When the normality condition was met, a Student's t-test was applied. When normality was not met, the non-parametric equivalent, the Wilcoxon signed-rank test, was used. The significance level was set at 5% ($p < 0.05$). The values presented are the means of the 13 participants plus or minus (±) the standard deviations.

3. Results

3.1. Muscular activity

3.1.1. Task 1: Holding a power drill above the head

The condition with the exoskeleton (Figure 6) showed a significant reduction in muscle activity of the anterior deltoid by 39.8% ($p < 0.001$), the biceps brachii by 58.1% ($p = 0.001$), the triceps brachii by 45.3% ($p < 0.001$), the clavicular portion of the pectoralis major by 57.4% ($p < 0.001$), the latissimus dorsi by 24.9% ($p = 0.027$), and the upper trapezius by 25.8% ($p < 0.001$) compared to the condition without the exoskeleton. However, there was no significant change in the activity of the longissimus during this task ($p = 0.266$).

3.1.2. Task 2: Load handling in vertical plane

Similarly, during the task of load displacement in the vertical plane, wearing the exoskeleton resulted in a significant reduction in the muscle activity of the anterior deltoid by 27.7% ($p < 0.001$), biceps brachii by 23.1% ($p = 0.015$), triceps brachii by 11.1 % ($p = 0.014$), major pectoralis by 17.2 % ($p = 0.002$), and upper trapezius by 11.5 % ($p = 0.011$). However, the activity of the latissimus dorsi ($p = 0.258$) and longissimus ($p = 0.77$) did not show a significant change for this task.

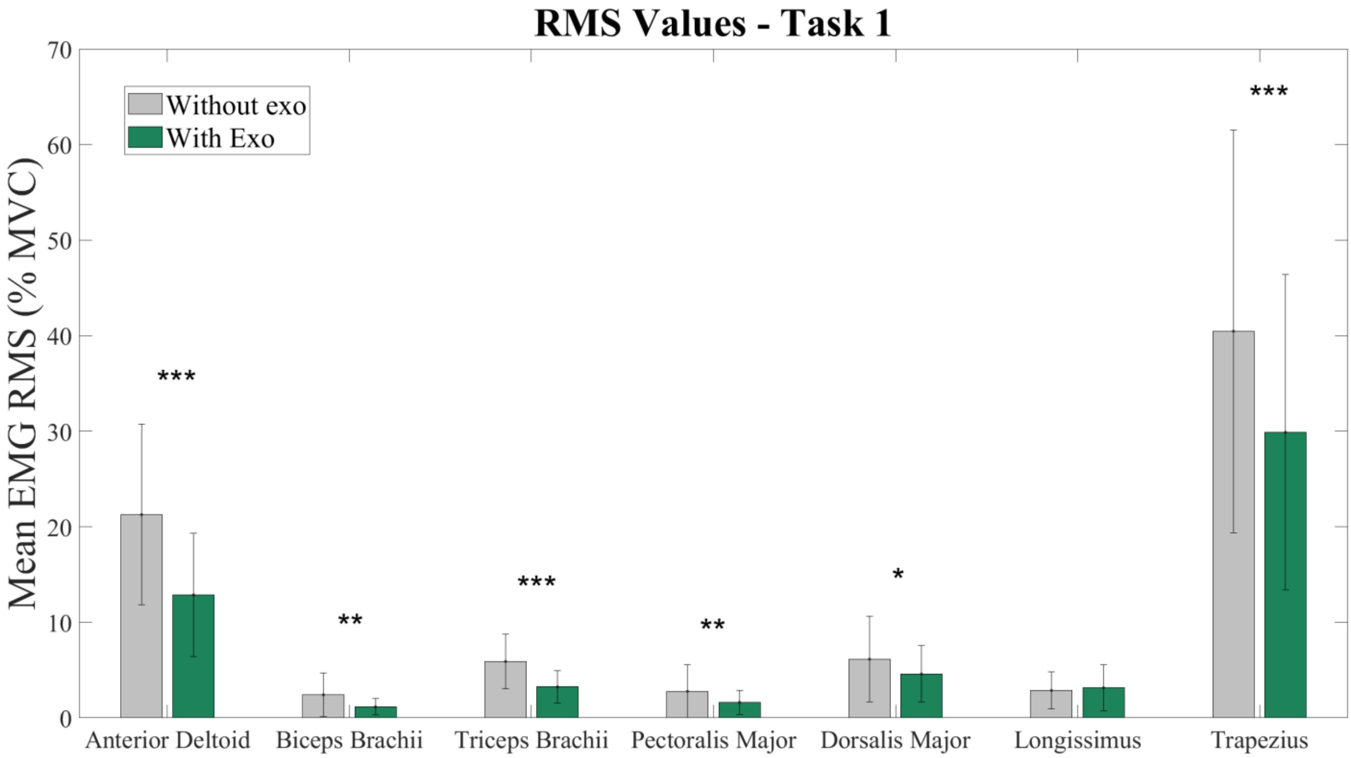


*Figure 6: Values of muscular activation normalized by MVC without and with exoskeleton for holding a power drill above the head task. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.*

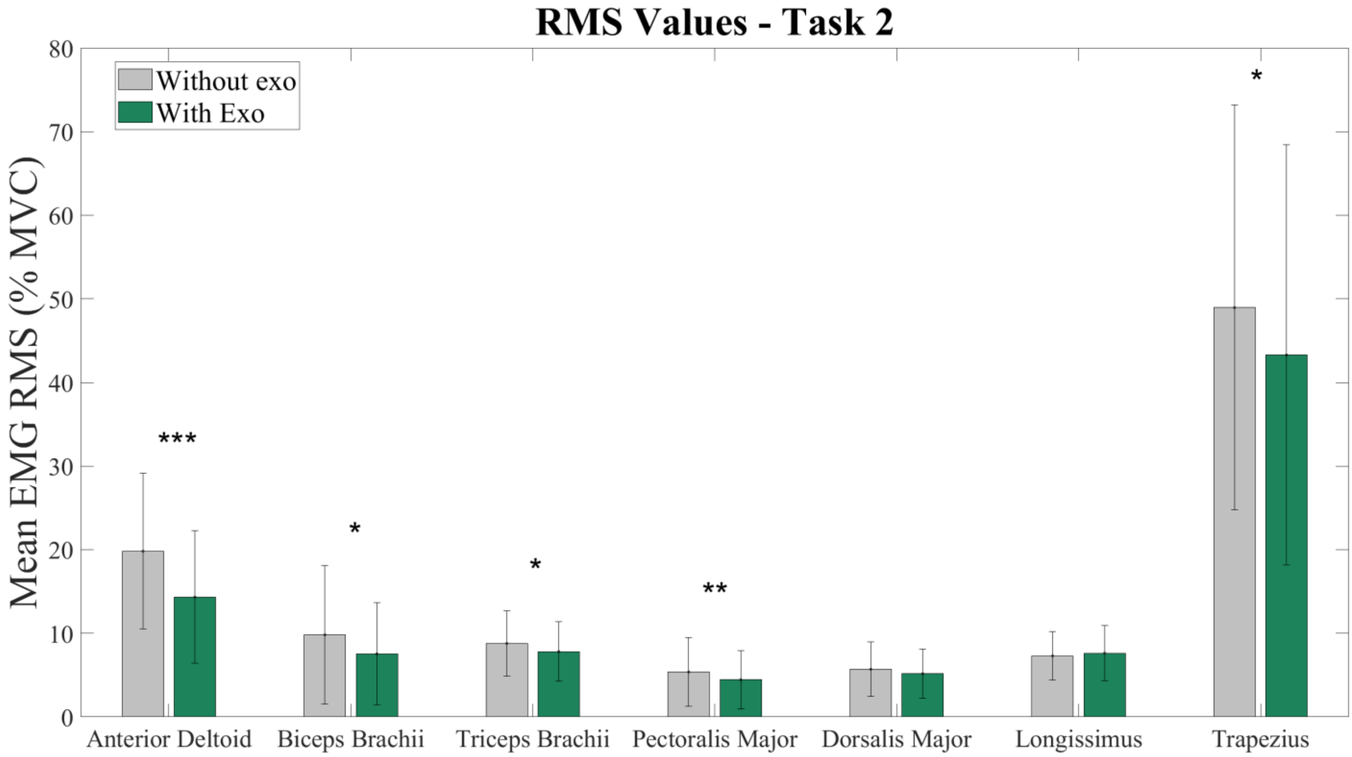


*Figure 7: Values of muscular activation normalized by MVC without and with exoskeleton for handling in vertical plane task. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$*

3.2. Kinematics

3.2.1. Task 1: Holding a power drill above the head

The kinematic data analysis for task 1 (Figure 8) shows a significant reduction in trunk extension at the thoracic level (T8) from 9.5° to 7.1° (-25%). Regarding the shoulder (Figure 9), the amplitude of internal rotation is significantly ($p < 0.001$) higher with the exoskeleton. On average, for task 1, this represents an increase from 49.1° to 75.8° (+35.3 %) of internal rotation. Additionally, there was a significant increase in shoulder adduction from 23.2° to 14.3°, a decrease of 38.4 %, and an average of 9° of adduction ($p = 0.017$) (Figure 9).

3.2.2. Task 2: Load handling in vertical plane

The analysis of kinematic data for task 2 reveals a significant increase in the average shoulder internal rotation amplitude from 23.4° (± 11.1°) to 41.9° (± 13.1°), representing a 44.2% ($p < 0.001$) increase (Figure 10). No significant differences were observed for other shoulder and trunk angles.

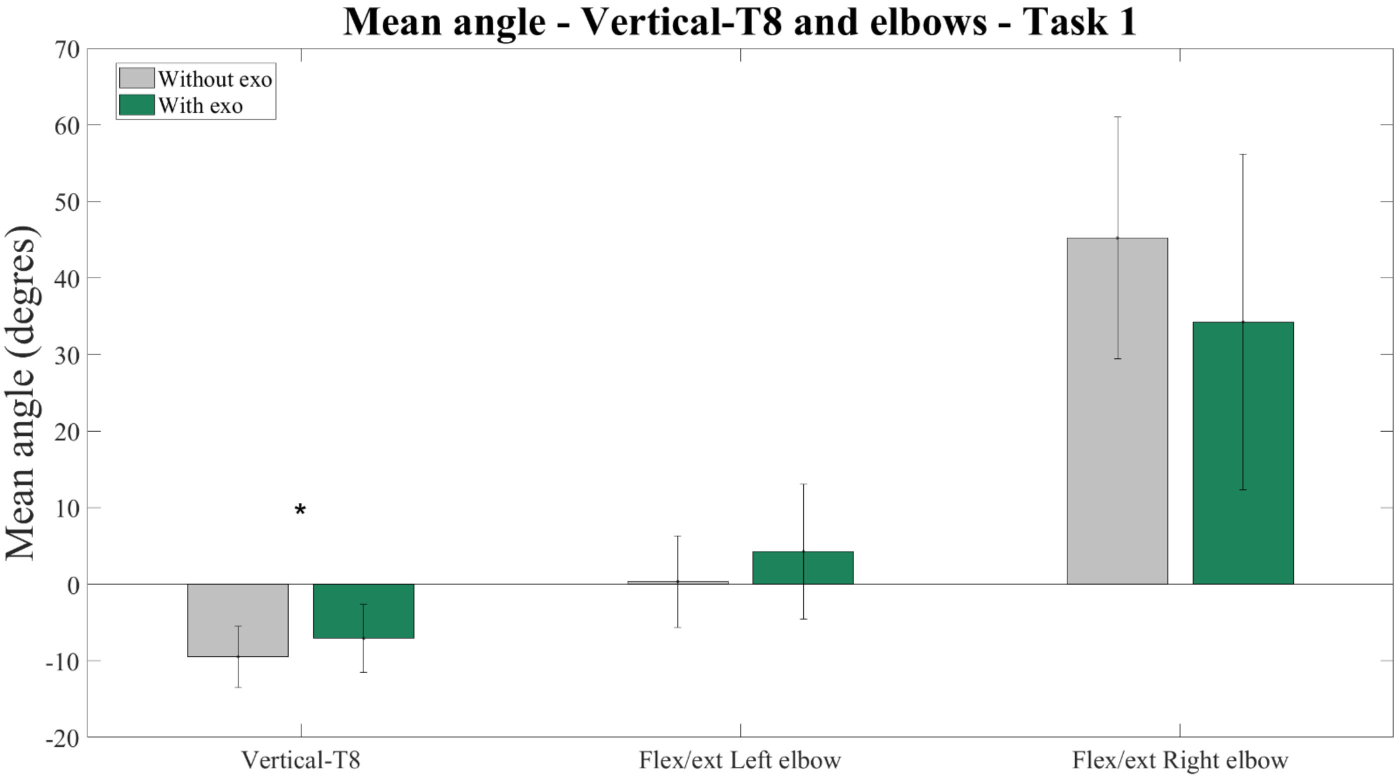


*Figure 8: Values of mean angles of upper limb and T8-vertical Values of mean angles of upper limb and T8-vertical with and without exoskeleton for the holding a power drill above the head task. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Positive angle = flexion. Negative angle = extension.*

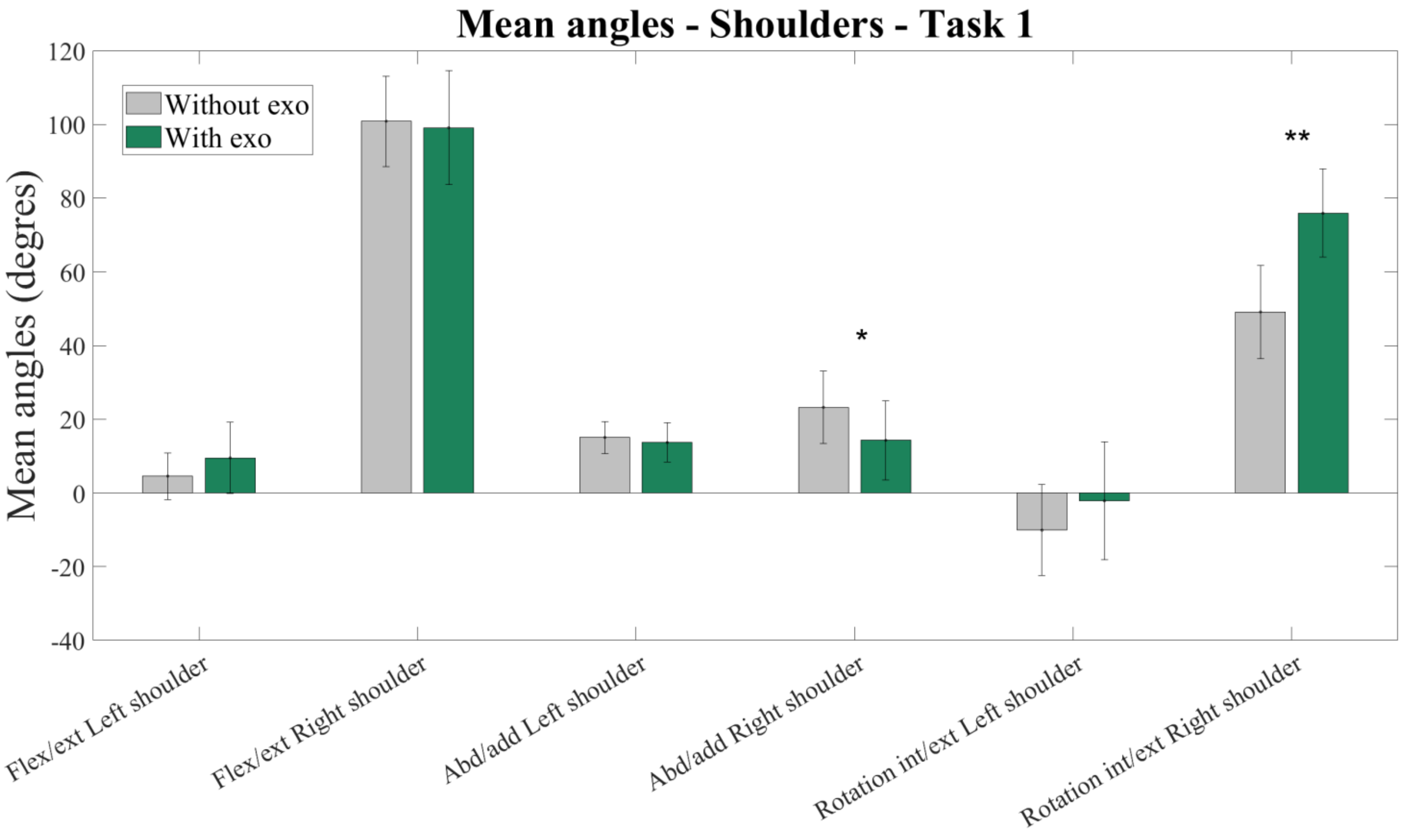


*Figure 9: Values of mean angles of shoulders with and without exoskeleton for the holding a power drill above the head task. * = p < 0.05; ** = p < 0.01; *** = p < 0.001. Positive angle = flexion or abduction or internal; Negative angle = extension or adduction or external. Flex = Flexion; Ext = Extension; Abd = Abduction; Add = Adduction; Int = Internal; Ext = External.*

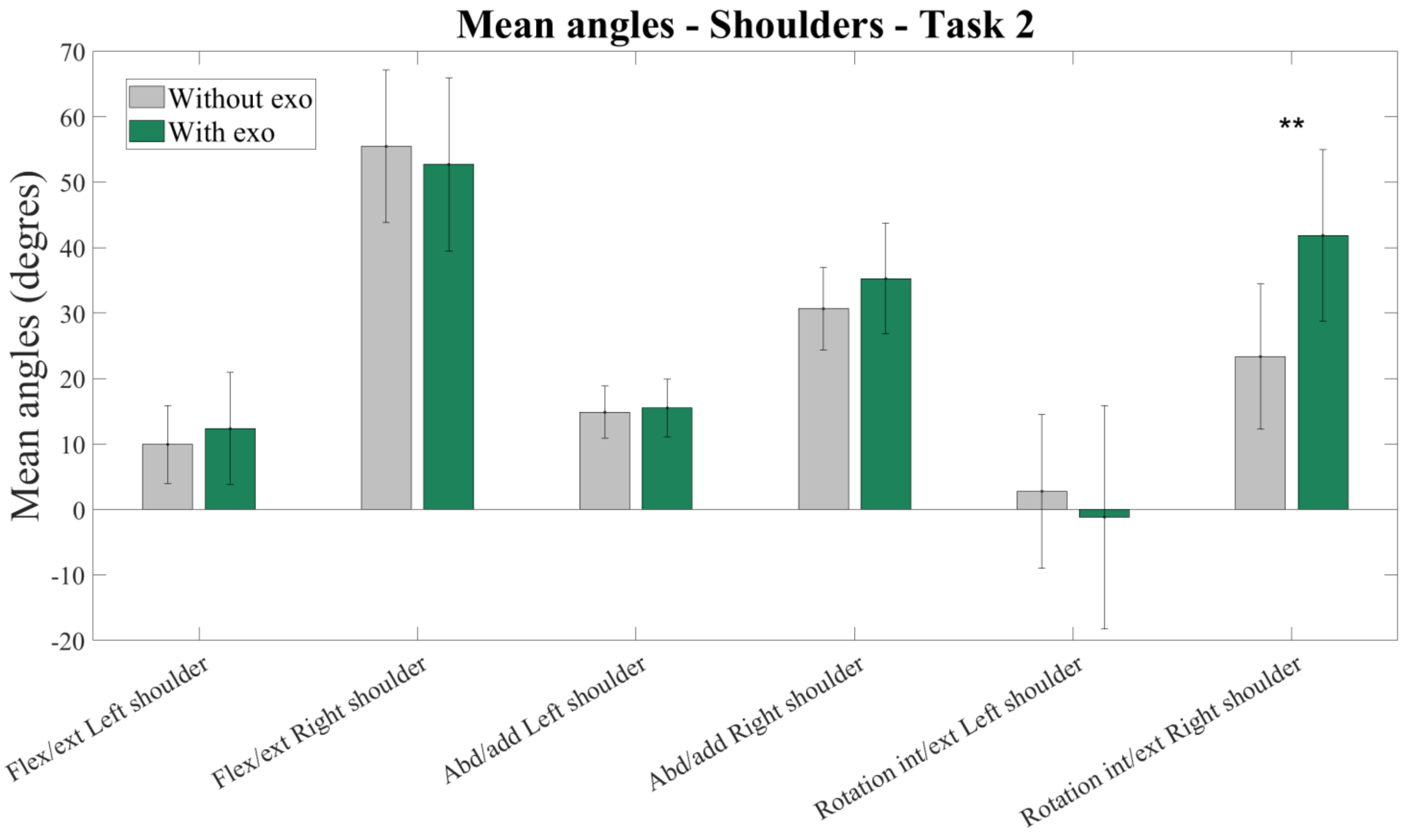


*Figure 10: Values of mean angles of shoulders with and without exoskeleton for the handling in vertical plane task. * = p < 0.05; ** = p < 0.01; *** = p < 0.001. Positive angle = flexion or abduction or internal; Negative angle = extension or adduction or external. Flex = Flexion; Ext = Extension; Abd = Abduction; Add = Adduction; Int = Internal; Ext = External.*

3.3. Postural balance

Regarding the COP velocities (CoPv), there was a non-significant increase with exoskeleton during task 1 from 0.007 m/s to 0.011 m/s (+3.8 %, p = 0.437). While, during task 2, there was a significant decrease in the center of pressure velocity (CoP_V) from 0.049 m/s to 0.045 m/s *i.e.* - 8.6%, (p = 0.039) with exoskeleton.

3.4. Perceived discomfort

The results related to the subjective evaluation of the perceived global discomfort on a maximum score of 10 were observed in both conditions (without and with exoskeleton). For Task 1, the average discomfort rating was 3.11 (± 0.92) without the exoskeleton and 2.73 (± 1.29) with the exoskeleton, but this difference was not statically significant (p = 0.191). For task 2, the average rating was 2.73 (± 0.75) without the exoskeleton and 2.30 (± 0.99) with the exoskeleton, and again the difference was not statistically significant (p = 0.087).

4. Discussion

4.1. Muscular Activity

The electromyographic (EMG) results highlight the effect of the exoskeleton on muscle activity. The significant reductions in EMG values for the anterior deltoid by 39.8% and 27.7% respectively for task 1 and task 2 are consistent with the literature, where the phenomenon varies from 25% to 55% depending on the task type and level of assistance [13]–[15], [18], [20]. The activity of the biceps brachii, involved in the movement of flexion, is also reduced [20], showing a decrease of 62% during a task involving holding a load above the head. The activity of the pectoralis major, an effector muscle for flexion, with its clavicular fibers participating in shoulder flexion, is reduced with the exoskeleton during both tasks. These results demonstrate that the exoskeleton reduces the muscular strain at the shoulder. The average RMS values of the EMG signal for the trapezius seem unusually high on Figures 6 and 7 compared to the literature. This difference can be explained by the fact that the values expressed as a percentage of MVC are highly influenced by the execution of a voluntary contraction, which in our case was probably submaximal for the trapezius. Therefore, the average RMS values of the trapezius do not reflect reality. Nevertheless, there is a significant decrease in muscle activation in the trapezius during the execution of both tasks with the exoskeleton. The overall reduction in muscle activity for the muscles involved in both tasks illustrates the decrease in physical stress thanks to the assistance of the HAPO UP on the upper limbs.

The results obtained in this study are based on loads of 1 to 2 kg. However, it is assumed, in line with the study by Theurel and Desbrosses [16], that for heavier loads, the assistance could be equally effective.

Some studies suggest that the use of upper limb exoskeletons can lead to an increase in the activity of stabilizing muscles or erector spinae [13], [14]. In agreement with Theurel et al., (2018), our present study shows no significant difference in the activity of the longissimus (erector spinae) [21].

Similarly, wearing an exoskeleton can lead to overactivation of the antagonist muscles to the flexion movement, such as the triceps brachii and the latissimus dorsi [14], [16]. Indeed, the study by

Theurel et al. (2018) reported an increase in the average workload of the triceps brachii by 95% and 116% with an exoskeleton during handling tasks [21]. On the contrary, the study by Rashedi et al., (2014) showed, for another exoskeleton, a decrease in triceps brachii muscle activity by about 40%. The results of our study are in line with Rashedi et al., (2014) as it has been shown that the HAPO UP reduces the demand on the triceps brachii by 45.3% and 11.1% for tasks 1 and 2, respectively [14]. This decrease can be explained by the fact that the triceps brachii is involved in stabilizing the arm during overhead tasks and is not constrained by the assistance during the movement of arm retropulsion. The latissimus dorsi, which participates in the flexion movement, is also influenced by wearing the exoskeleton since a reduction in its activity is observed in task 1. It is assumed, in agreement with the study by B. M. Otten et al., that this muscle, like the triceps brachii, is involved in stabilizing the arm during flexion [12].

These effects and non-effects can be explained by an optimally applied assistance force tailored to the weight of the arms, which limits the risk of opposing the retropulsion movement of the arm. The presence of a passive disengagement mechanism also limits the risk of opposing the exoskeleton in the lower arm position. Moreover, the reductions in the demand on the triceps brachii and latissimus dorsi can be attributed to a decreased need for shoulder stabilization already provided by the exoskeleton.

4.2. Kinematics

The changes in shoulder kinematics during a prolonged holding task (task 1) appear to indicate a tendency for the elbow to move inward (adduction). Following this modification in shoulder kinematics, it is assumed that the user naturally adopts a comfortable posture where the assistance is optimal. Moreover, this modification bears similarities to the study by Maurice et al. [18], which reported a more pronounced shoulder abduction movement with a similar exoskeleton to the HAPO UP. These results collectively suggest that the exoskeleton is likely to modify the user's abduction/adduction amplitude without impeding their freedom of movement. The adjustment of the PAD assistance position on the external side of the humerus may be the causative factor of this kinematic change. Conversely, the study by Alabdulkarim and Nussbaum noted that users equipped with an exoskeleton keep their shoulder slightly abducted to avoid being constrained by the exoskeleton's force during arm retraction towards the neutral position [11].

The increase in shoulder internal rotation amplitude observed in both tasks is presumed to be due to the adaptation of a different handling kinematics, placing the elbow in a higher position than the wrist during the movement. This hypothesis could be justified by the presence of assistance on the external and lower part of the user's humerus during the task of moving loads in the vertical plane.

Lastly, the significant decrease in T8 extension compared to the vertical component is not in line with the study by Maurice et al. (2020) where no significant difference was found for this parameter. It is presumed that this change is also related to a comfortable posture in which the user places themselves to maintain a prolonged posture [18].

4.3. Postural balance

The decrease in mean CoPv (Center of Pressure velocity) for task 2 with the exoskeleton suggests a modification in postural control. This reduction is likely related to a decrease in the occurrence of fatigue, which is favorable for reducing balance disturbances as suggested in the study by Maurice [18].

Furthermore, it is presumed that the mass of the exoskeleton and its distribution may impact this balance parameter. Studies based on the evaluation of particularly heavy exoskeletons illustrate a tendency to have a greater impact on postural control compared to a lighter exoskeleton with better weight distribution [11], [14]. In this present study, the mass of the exoskeleton is relatively low (1.67 kg). Additionally, the produced torque at the shoulder is constant. Therefore, it can be assumed that the impact of the PAD is less significant on the user's sensory perception [16]. As a result, the user's postural control is not degraded by the mass of the exoskeleton. These results are consistent with studies employing a lightweight exoskeleton [16], [18].

Lastly, the results in terms of postural balance have shown that the PAD has little impact on the user's perception of focal movement for loads of 2 kg or less [16].

4.4. Perceived discomfort

The wearing of the exoskeleton, despite the effective assistance it provides, does not significantly reduce the perceived discomfort in the upper limbs. These results do not fully align with the scientific literature synthesized by the study of Theurel and Desbrosses [16], which showed a decrease in perceived discomfort in the upper limbs. It is possible that the tasks in this present study did not last long enough or were not demanding enough to experience the benefits of the exoskeleton. Additionally, it is conceivable that any reduction in perceived discomfort is offset by an increase in discomfort related to the exoskeleton itself.

5. Limits

In general, the present study suggests that wearing the HAPO UP exoskeleton may reduce certain risk factors associated with the development of musculoskeletal disorders (TMS-MS). However, some limitations need to be highlighted. Firstly, the study population is not perfectly representative of expert workers. Additionally, it contained a minority of female participants (N = 3) compared to the number of male subjects (N = 10), even though the female population is more exposed to the risks of MSD [4]. Achieving gender parity in this study would have strengthened the results for the entire population. Moreover, caution should be exercised when generalizing these findings to older workers, injured individuals, and/or those with higher body mass.

Furthermore, all participants are part of the ErgoSanté company. Although they are not directly involved in the exoskeleton's design, it could represent a potential bias in the study, particularly regarding subjective results.

6. Conclusion

The use of the HAPO UP exoskeleton for overhead work tasks and vertical load handling is beneficial in reducing the activity of the muscles primarily involved in such tasks (anterior deltoid, biceps brachii, triceps brachii, upper trapezius, and pectoralis major). The exoskeleton does not cause unwanted muscle activation. The HAPO UP tends to influence the kinematics of the upper limbs without causing discomfort or impeding the user's freedom of movement. Furthermore, the exoskeleton does not disrupt postural balance and may even be beneficial in dynamic conditions.

The exoskeleton meets expectations in terms of reducing physical strain without any detrimental effects on the user. The device is non-intrusive and does not generate discomfort. A field study would be the logical next step in assessing the acceptance of the exoskeleton, which becomes an important aspect of prevention [22].

Conflicts of interest

Authors are affiliates with the company which designs, manufactures and sells the exoskeleton tested.

References

[1] European Commission. Eurostat et European Commission. Directorate-General for Employment, Social Affaires and Equal Opportunities, *Health and safety at work in Europe (1999-2007) : a statistical portrait*. LU : Publications Office, 2010. Consulté le: 13 avril 2023. [En ligne]. Disponible sur: https://data.europa.eu/doi/10.2785/38630

[2] « TMS : définition et impact ». https://www.ameli.fr/entreprise/sante-travail/risques/troubles-musculosquelettiques-tms/tms-definition-impact.

[3] « L’exposition des salariés aux maladies professionnelles en 2012 | Dares ». https://dares.travail-emploi.gouv.fr/publications/l-exposition-des-salaries-aux-maladies-professionnelles-en-2012

[4] M. Aptel, A. Aublet-Cuvelier, et J.-C. Cnockaert, « Les troubles musculosquelettiques du membre supérieur liés au travail », *Revue du Rhumatisme*, vol. 69, nº 12, p. 1181-1190, déc. 2002, doi: 10.1016/S1169-8330(02)00438-6.

[5] S. Poiraudeau, M.-M. Lefevre Colau, F. Fayad, F. Rannou, et M. Revel, « Lombalgies », *EMC - Rhumatologie-Orthopédie*, vol. 1, nº 4, p. 295-319, juill. 2004, doi: 10.1016/j.emcrho.2004.04.001.

[6] Y. Roquelaure, « Troubles musculo-squelettiques et facteurs psychosociaux au travail — ».

[7] J. Mayer, T. Kraus, et E. Ochsmann, « Longitudinal evidence for the association between work-related physical exposures and neck and/or shoulder complaints: a systematic review », *Int Arch Occup Environ Health*, vol. 85, nº 6, p. 587-603, août 2012, doi: 10.1007/s00420-011-0701-0.

[8] H. Miranda, L. Punnett, E. Viikari-Juntura, M. Heliövaara, et P. Knekt, « Physical work and chronic shoulder disorder. Results of a prospective population-based study », *Annals of the Rheumatic Diseases*, vol. 67,

n° 2, p. 218-223, févr. 2008, doi: 10.1136/ard.2007.069419.

[9] P. Frost *et al.*, « Risk of shoulder tendinitis in relation to shoulder loads in monotonous repetitive work », *Am J Ind Med*, vol. 41, n° 1, p. 11-18, janv. 2002, doi: 10.1002/ajim.10019.

[10] F. Bailly, A. Petit, S. Kab, V. Foltz, M. Badard, et B. Fautrel, « Prévalence des troubles musculo-squelettiques dans la population française », *Revue du Rhumatisme*, vol. 89, p. A20-A21, déc. 2022, doi: 10.1016/j.rhum.2022.10.015.

[11] S. Alabdulkarim et M. A. Nussbaum, « Influences of different exoskeleton designs and tool mass on physical demands and performance in a simulated overhead drilling task », *Applied Ergonomics*, vol. 74, p. 55-66, janv. 2019, doi: 10.1016/j.apergo.2018.08.004.

[12] B. M. Otten, R. Weidner, et A. Argubi-Wollesen, « Evaluation of a Novel Active Exoskeleton for Tasks at or Above Head Level », *IEEE Robotics and Automation Letters*, vol. 3, n° 3, p. 2408-2415, juill. 2018, doi: 10.1109/LRA.2018.2812905.

[13] S. Kim, M. A. Nussbaum, M. I. Mokhlespour Esfahani, M. M. Alemi, S. Alabdulkarim, et E. Rashedi, « Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – "Expected" effects on discomfort, shoulder muscle activity, and work task performance », *Applied Ergonomics*, vol. 70, p. 315-322, juill. 2018, doi: 10.1016/j.apergo.2018.02.025.

[14] E. Rashedi, S. Kim, M. A. Nussbaum, et M. J. Agnew, « Ergonomic evaluation of a wearable assistive device for overhead work », *Ergonomics*, vol. 57, n° 12, p. 1864-1874, déc. 2014, doi: 10.1080/00140139.2014.952682.

[15] P. Yin, L. Yang, S. Qu, et C. Wang, « Effects of a passive upper extremity exoskeleton for overhead tasks », *Journal of Electromyography and Kinesiology*, vol. 55, p. 102478, déc. 2020, doi: 10.1016/j.jelekin.2020.102478.

[16] J. Theurel et K. Desbrosses, « Occupational Exoskeletons: Overview of Their Benefits and Limitations in Preventing Work-Related Musculoskeletal Disorders », *IISE Transactions on Occupational Ergonomics and Human Factors*, vol. 7, n° 3-4, p. 264-280, oct. 2019, doi: 10.1080/24725838.2019.1638331.

[17] N. Sylla, V. Bonnet, F. Colledani, et P. Fraisse, « Ergonomic contribution of ABLE exoskeleton in automotive industry », *International Journal of Industrial Ergonomics*, vol. 44, n° 4, p. 475-481, juill. 2014, doi: 10.1016/j.ergon.2014.03.008.

[18] P. Maurice *et al.*, « Objective and Subjective Effects of a Passive Exoskeleton on Overhead Work », *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, n° 1, p. 152-164, janv. 2020, doi: 10.1109/TNSRE.2019.2945368.

[19] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, et G. Rau, « Development of

recommendations for SEMG sensors and sensor placement procedures », *Journal of Electromyography and Kinesiology*, vol. 10, n° 5, p. 361-374, oct. 2000, doi: 10.1016/S1050-6411(00)00027-4.

[20] K. Huysamen, T. Bosch, M. de Looze, K. S. Stadler, E. Graf, et L. W. O'Sullivan, « Evaluation of a passive exoskeleton for static upper limb activities », *Applied Ergonomics*, vol. 70, p. 148-155, juill. 2018, doi: 10.1016/j.apergo.2018.02.009.

[21] J. Theurel, K. Desbrosses, T. Roux, et A. Savescu, « Physiological consequences of using an upper limb exoskeleton during manual handling tasks », *Applied Ergonomics*, vol. 67, p. 211-217, févr. 2018, doi: 10.1016/j.apergo.2017.10.008.

[22] « Acceptation des exosquelettes par les opérateurs : étude exploratoire - Archive ouverte HAL ». https://hal.science/hal-03079985/ (consulté le 7 avril 2023).