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# Motion capture and myoelectric multimodal measurements during static and dynamic bending tasks using a back-assisting exoskeleton: a preliminary study

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## ABSTRACT

Work-related musculoskeletal disorders are causing occupational diseases. While allowing them to control the execution of their picking task, one solution to physically relieve workers performing trunk flexions is to assist them with an exoskeleton. This preliminary study focuses on the determination of the appropriate measurements systems (motion capture and electromyography) to characterize dedicated trajectories of movements responsible of lower back pathologies. Three tests have been realized with and without a back-assisting exoskeleton for loaded box picking. The results of the study help us to understand which body strategies were used to perform the same task from one individual to another under different conditions. This preliminary study validates this multimodal approach to show the use of a back-assisting exoskeleton for posture harness in dynamic conditions.

**Keywords:** exoskeleton, posture harness, motion capture, electromyography, multimodal analysis.

## 1. INTRODUCTION

Musculoskeletal disorders (MSDs) have many causes, but work activity frequently plays a role in their occurrence, maintenance or aggravation. They result from an imbalance between the body's physical capacities and the stresses and strains to which the body is exposed. They can appear and occur rapidly. However, they most often develop gradually after a long period of intensive use of the affected parts of the body.

There are many factors involved in MSDs, including organizational, cognitive, biomechanical and individual factors. As regards biomechanical factors, these are movements involving inappropriate force, high repetitiveness of movement and awkward posture. Organizational factors are related to the pace of work, working hours, and the content of the work (too short a deadline). For example, poor lighting when checking the quality of parts can cause an employee to bend his or her neck excessively to see better (Assurance Maladie, 2019)[1].

The cognitive or psychosocial factor is based on the way in which the work is perceived by the employees, such as dissatisfaction with monotonous work, the tension generated by the deadlines to be met, the lack of professional recognition, poor social relations, the lack of support from the hierarchical superior and colleagues or job insecurity.

The last factor, individual, favors the occurrence of MSDs. Age is responsible for an ageing of the peri-articular structures. Physical and physiological fragility (diabetes, rheumatism, fatigue, overweight, reduced immunitý) or psychological fragility are to be taken into account in the appearance of musculoskeletal disorders.

These pathologies develop rapidly when the biomechanical demands at work are greater than the physical capacity of the worker for repetitive movements in most cases. They can also be linked to extreme posture according to Luttman [2], who explains that when a high effort is required, extreme joint angles are involved in a task performed in depth. As a result, muscular efforts are then at the origin of an increase in the employee's energy expenditure. In France, MSDs of the upper limb and low back pain are recognized as occupational diseases (ODs) which represent approximately 12.2 million lost work days, or 57,000 full-time jobs [3].

Despite the development of information on occupational diseases in companies, not all MSD pathologies are reported, although 87% of occupational diseases (OD) and 20% of work accidents (WA) (sprains, lumbagos, herniated discs, etc.) are related to MSDs (Assurance Maladie, 2020)[4].

This increase in the number of cases of MSDs now makes it essential to prevent them in the workplace.

While the multiple factors at the origin of MSDs make it complex to implement effective prevention, there are prevention solutions applicable in each sector of activity through technological innovations impacting on the main biomechanical risk factors.

The objective is to detect in which form the pathology appears. Most of the time it is revealed during work in a maintained position, high repetitiveness of gestures, excessive efforts or extreme joint amplitudes.

These indicators are often seen in handling or load-carrying tasks in the professional world.

The handling of loads has always been a concern for society. Despite improvements in working conditions from year to year, there are still occupations where manual handling is still preserved, having the greatest impact on workers' health (Arnaudo et al., 2004)[5]. The loads carried correlated to the number of effective hours of manual handling are the source of risk factors for the development of low back pain, sciatica and in general MSD at work.

Exoskeletons are mostly designed according to the laws of physics of motion and materials, but there are still important scientific barriers to understanding understand human motion control and human-machine interaction that need to be addressed. Moreover, the disorganization of companies caused by absences from work will lead to a reduction in the performance of companies where handling is a major factor. A generalized device should be designed for the prevention of MSDs and, in particular, assistance during load carrying capable of relieving the lumbar area. However, there is a lack of validation of physical assistance devices for the upper limb, making it possible to label the devices and ensure that they work properly.

INRS is following this approach with their study on the exoskeleton at work [6]. The objective was to compare different physical assistance devices for several identical load-bearing tasks. It was observed that it is necessary to identify the work task to be assisted in order to find an exoskeleton that is perfectly adapted to the movements required by the task.

A physical assistance device must be perfectly suited to its use in order to obtain positive results.

Benefits observed with the use of exoskeletons in previous studies vary from -10% to -80% in terms of reduction of muscle strain. This phenomenon can be explained by the interaction between the physical assistance requirements associated with the task, the design characteristics, the assistance performance of the exoskeleton, and the individual characteristics [7].

Thus, when designing a physical assistance device, it is essential to carry out tests to analyze the effects of the device from one individual to another before marketing it.

We have therefore analyzed the effectiveness of a new Physical Assistance Device (PAD), called "HAPO" from the company Ergosanté Technologie, through objective parameters allowing us to quantify its action (kinematics, muscular activity, heart rate) and subjective parameters (feeling survey) allowing us to describe the personal acceptance of such a device in the professional environment in conditions with and without an exoskeleton.

The main objective of this preliminary research study is to create a laboratory validation method to study in depth the effects caused by an exoskeleton in order to follow up on tests in the field. These analyses would make it possible to validate a device and to study the phenomena capable of limiting or preventing occupational diseases linked to biomechanical constraints.

## 2. PROTOCOL

### 2.1 Participants

N= 2 volunteers (2 males) with a age of 21 and 23 years old, with a weight of 85.5 and 77.5 kg, who had never worn a posture harness.

Volunteer participants completed an informed consent form prior to the experiment. The participants had no documented history of locomotion and balance disorders nor medical conditions that could affect postural control in the last two years.

The experiment was carried out in the laboratory of applied optics at Euromov Digital Health in Motion, IMT Mines, Alès (Gard, France).

## 2.2 Physical Assistance Device: HAPO

The posture harness evaluated in this study is the HAPO, designed by Ergosanté Technologie (Gard, France) and marketed in March 2020. The HAPO is a lightweight (1.2 kg) restraint physical assistance device that provides support torque to the user's back, transferring stresses at the sleeves to the thighs.

The technology of the HAPO is based on a spring composed of unidirectional fiberglass strands along the length of the spring. The matrix of the component is epoxy resin. This material allows for a long rod length with a large deformation. This is the source of the spring effect. The deformation of the spring stores energy which is then transferred during the upward phase of the torso when leaning forward or carrying a load.

Figure 1. HAPO posture harness, Ergosanté Technologie

## 2.3 Electromyogram (EMG)

Electromyograms allow the intensity of the electrical signal provided by the muscles to be recovered. It should be noted here that these are surface electromyograms (EMG). For our study, we used Delsys EMGs with acquisition frequency of 1000 Hz (Delsys Incorporated, Natick, USA).

The EMG allows to analyze the reaction of the subjects to the effect of the HAPO. 12 electrodes have been placed on 9 different muscle heads (Figure 2).

These EMG devices measure muscle activity in the upper limbs of the right arm of the biceps brachii, triceps brachii and anterior deltoid muscles during load-bearing and static forward arm movements. The right and left upper trapezius muscles, the right and left longissimus muscles and the right and left lumbar muscles allow the analysis of the muscular load on the back.

Finally, three last electrodes were placed on the rectus femoris, the long head of the biceps brachii and the soleus, which will be relevant for determining whether there is a change in effort in the lower limbs. The placement of the surface electrodes will be done using the "SENIAM.org" database. The electrodes were placed by abrading the skin with alcohol.

Figure 2. EMG placement

## 2.4 Motion Capture system

To ensure complete measurements of interesting body displacements, 10 Miqus M3 (Qualisys, Goteborg, Sweden) cameras connected on standard PC with QTM software allow trunk-pelvis angular analysis and observation of spinal segment variations. This Qualisys system is a motion capture system using cameras and passive markers, including small reflective balls attached to the subject's body. Lens objectives of the camera system are equipped with LED array emitting in the near Infrared. Markers are then back reflecting this light into the camera objectives. After calibration by moving T-wand with two well-known distant markers into the measurement volume with calibrated L-shape equipped with 3 markers

The system offers ~0.5 mm accuracy for the analyzed movements within the calibrated volume (about 8m3). The position of the markers is based on the literature [8] and [9]. These locations will allow the assessment of the trunk flexion amplitude regarding to avoid the significant compression of the spine. Finally, the acquisition frequency (100Hz) of the system has been set to cope with the subject’s task displacements rate. M3 camera can reach up to 650fps in hi speed mode (0.5Mpixel) and 340fps in full FOV (2Mpixel, 1824x1088). These frame rates are given as markers rate and not image rate.

(a) (b) (c)

Figure 3. Motion capture: (a) Example of cameras setup in ready mode, (b) Focus on marker placement, (c) Global view

## 2.5 Heart rate monitor belt

There is a strong linear relationship between heart rate and energy expenditure (Université Médicale Virtuelle Francophone, UMVF, 2011)[10]. This will allow us to obtain information in case the HAPO has an impact on energy expenditure for the same task. Through a Polar H10 belt & Polar V800 watch (Finland), the heart rate will be recorded using a sensor located on the sternum with 1Hz of acquisition frequency.

### 2.6 Survey on the feeling

A survey on the feeling of effort concerning the general use of the posture harness has been distributed to the participants. The subjective study (20 questions in total) was carried out based on INRS guidance on the acceptability of exoskeletons [11].

### 2.7 Procedure

The experiment consisted of two main tasks, a load bearing (lifting) task and a static torso bending task. The conditions of the experiment are three distinct statuses: "With HAPO engaged", "With HAPO disengaged" and "Without HAPO". The posture harness has an engagement system to activate or not the action of the springs.

Participants performed in first time a static 45-degree trunk flexion task with their arms extended forward for 2 minutes then in other time 20 repetitions of a 7.5 kg load-bearing task under the three conditions listed above. For the load-bearing task, participants had to carry a load from the ground, stand up and then put it back down. After performing the load-bearing task in the "HAPO engaged" condition, participants completed a questionnaire to assess PAD acceptance.

## 3. DATA ANALYSIS

### 3.1 Muscular Activity

The analyzed muscles data were processed using the EMG Works Analysis software from the Delsys EMG sensor. This software facilitated the EMG processing thanks to functions integrated into the EMG Works software allowing a low-pass Butterworth filtering, with a cut-off frequency of 20 Hz and of order 8.

This low-pass filtering was used to remove noise and artefacts from the signal probably due to sensor friction with the device.

In addition, the Root Mean Square (RMS) function was used to calculate the square root of the energy contained in the EMG signal for each sensor in order to give us a parameter allowing a very global quantification of the activity.

### 3.2 Kinematics: variation of Trunk-Pelvis angles

All motion capture recordings were exported and then processed with MATLAB software to isolate each movement based on the velocity profile.

The raw signal was segmented into sequences in order to perform the processing for each participant on all repetitions during the load-bearing tasks under all conditions. Once this step was completed, we sought to obtain the expression of the forward bending angle of the torso in the sagittal plane for each repetition.

The observed angle is the one created from a pelvic segment delimiting the anterior superior iliac spines and a segment connecting the sensors at the level of the spinous process of the cervical vertebra C7 and the middle of two markers located at the level of the lumbar zone. These two segments create an angle in the antero-posterior axis allowing us to measure the angular amplitude of flexion of the bust in the sagittal plane.

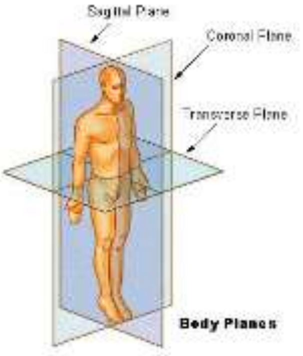


Figure 4. Body planes (from Wiktionary.org)

The isolated amplitude parameter is calculated from the difference between the max and min angles of each repetition: $\theta amplitude = \theta max - \theta min$

Both the movement time and the movement speed could also be selected and observed.

The movement time is calculated from the difference between the final time and the initial time of the repetition that was extracted during segmentation: $t_{mvt} = t_{fin} - t_{init}$.

The maximum velocity (peak velocity) of motion is obtained from the derivative of the position during each motion.

### 3.3 Heart Rate

The heart rate data recordings were processed with MATLAB software to isolate each task in each condition to obtain an average heart rate for the last 30 seconds of each condition.

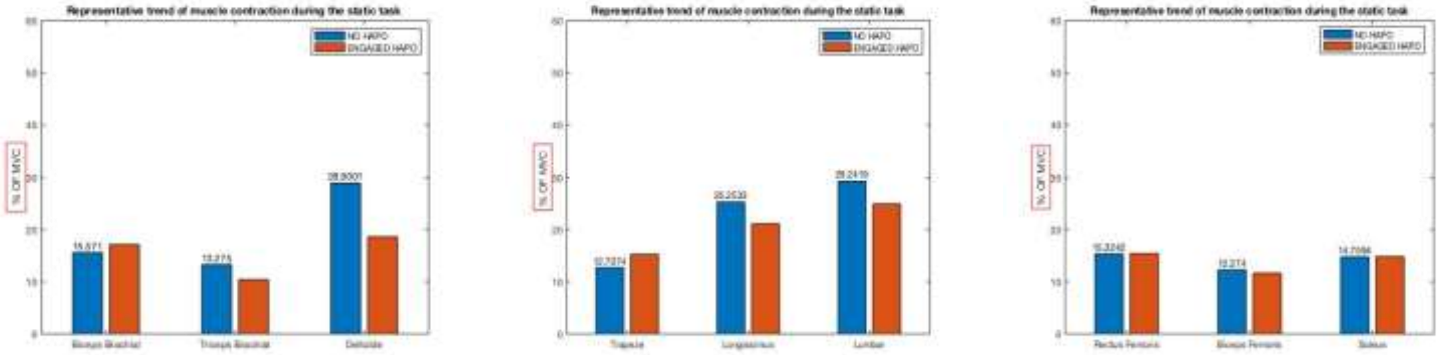
### 3.4 Subjective criteria: comfort and feedback survey

The feedback questionnaire survey allows us to quantify the level of satisfaction with the use of the HAPO and to determine areas of discomfort, if any, related to the different tasks in the study.

## 4. RESULTS

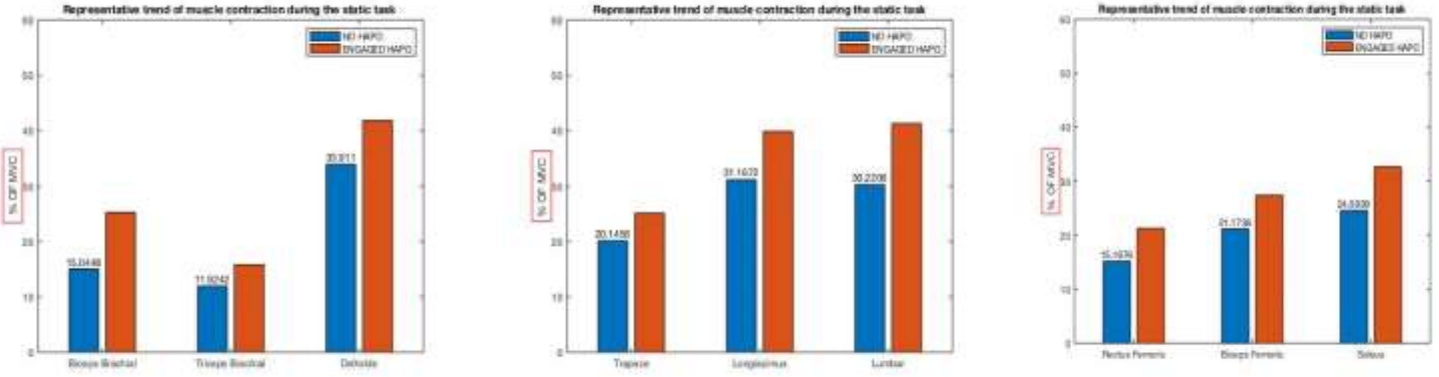
### 4.1 Muscular activity

The analysis of muscle activity was performed under two different tasks: a static task and a dynamic task. In the first case, the analysis of the static task for the condition with HAPO engaged and without HAPO, shows that the activity of the arms, back and lower limbs varies little with or without the device. These representations show that when subject 1 uses the HAPO engaged, his muscular activity is decreased. In subject 2, there is an increase in muscle activity.



(a) (b) (c)

Figure 5: Muscles contractions during static task in % of MVC for each muscle for subject 1. (a) upper limb muscle; (b) back muscle; (c) lower limb muscle.



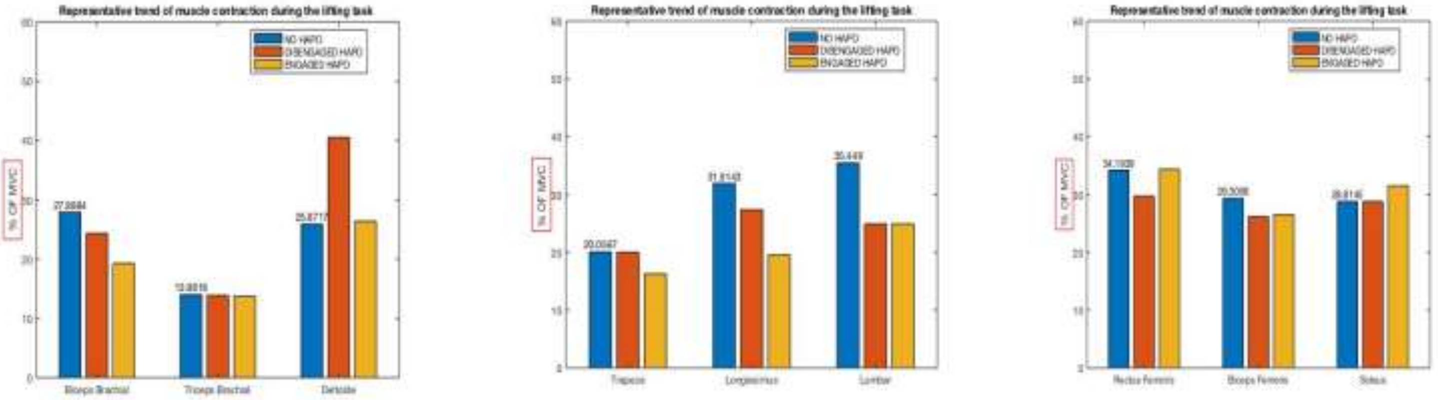
(a) (b) (c)

Figure 6: Muscles contractions during static task in % of MVC for each muscle for subject 2. (a) upper limb muscle; (b) back muscle; (c) lower limb muscle.

Secondly, during the load-bearing task, the three conditions are analyzed. The activity of the lower limbs does not vary greatly whether the subject is wearing the HAPO or not.

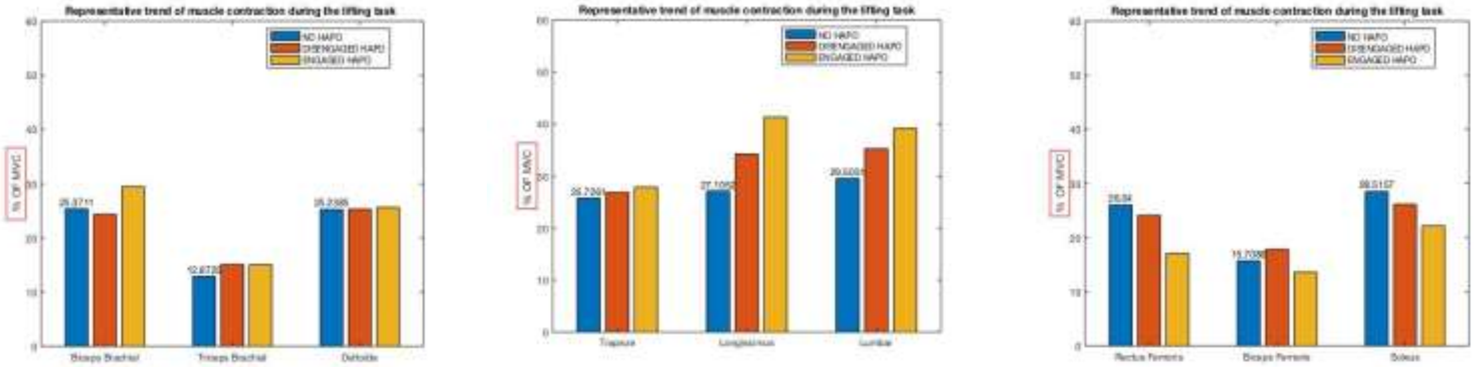
For subject 1, we see that at the level of the arms and the back, there is a decrease although there is a value of the deltoid muscle which is important when the HAPO is disengaged. The activity of erector spinae muscles and the squared muscle of the lumbar region decrease when the HAPO is worn.

Subject 2 has an increase in muscle load on the arms and back when wearing the HAPO.



(a) (b) (c)

Figure 7: Muscles contractions during load-bearing task in % of MVC for each muscle for subject 1. (a) upper limb muscle; (b) back muscle; (c) lower limb muscle.

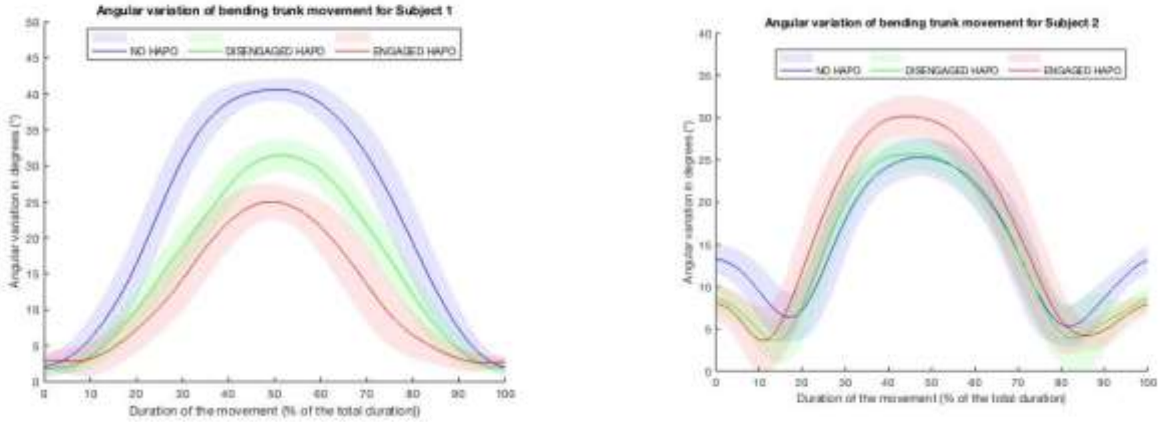


(a) (b) (c)

Figure 8: Muscles contractions during load-bearing task in % of MVC for each muscle for subject 2. (a) upper limb muscle; (b) back muscle; (c) lower limb muscle.

### 4.2 Kinematics

The kinematic results show the average angular evolution over time of each repetition. The average angle decreases with the wearing of the HAPO for Subject 1, which is the opposite for Subject 2. We also observe for both subjects a higher variability when the HAPO is engaged compared to when they are without the device.



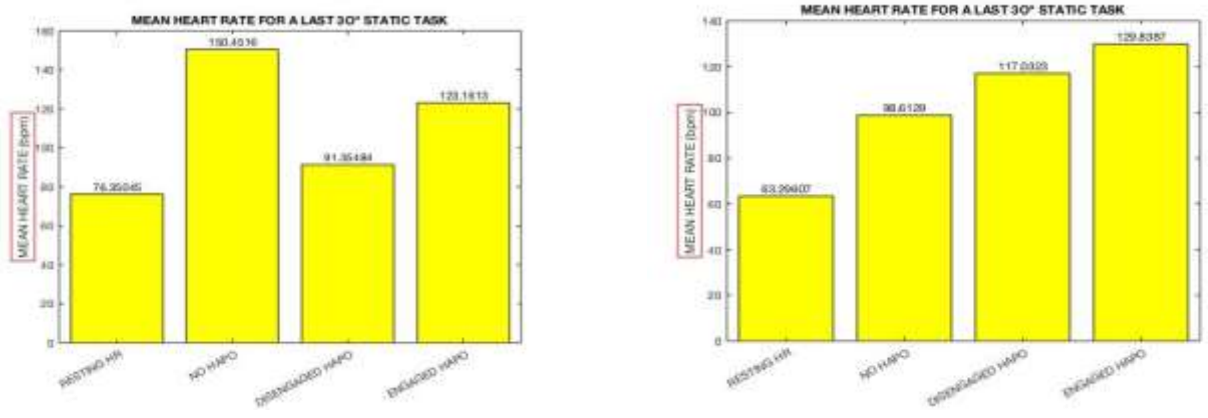
(a) (b)

Figure 9: Angular variation of bending trunk movement: (a) subject 1; (b) subject 2

### 4.3 Heart Rate

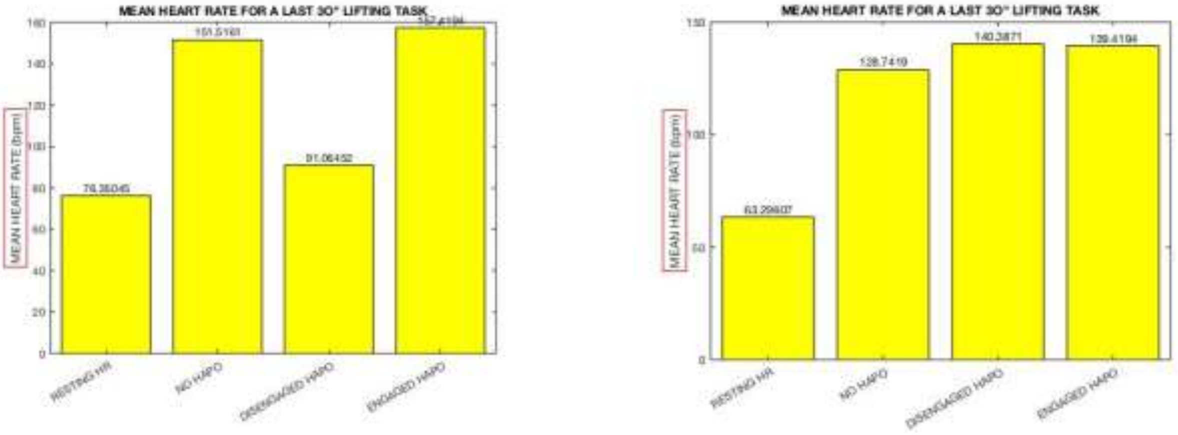
For Subject 1, our measurements show that wearing the HAPO during the load-bearing task increases lightly the heart rate during the last 30 seconds of each condition, while for the static task the rate decreases with the HAPO worn.

Subject 2 has an increased heart rate with the use of the device. The more active the HAPO is, the more the heart rate increases for the static task. For load bearing there is a slight increase when wearing the HAPO but the difference between active and inactive HAPO does not have a huge effect on the rate.



(a) (b)

Figure 10: Mean heart rate for a last 30 seconds static task: (a) subject 1; (b) subject 2

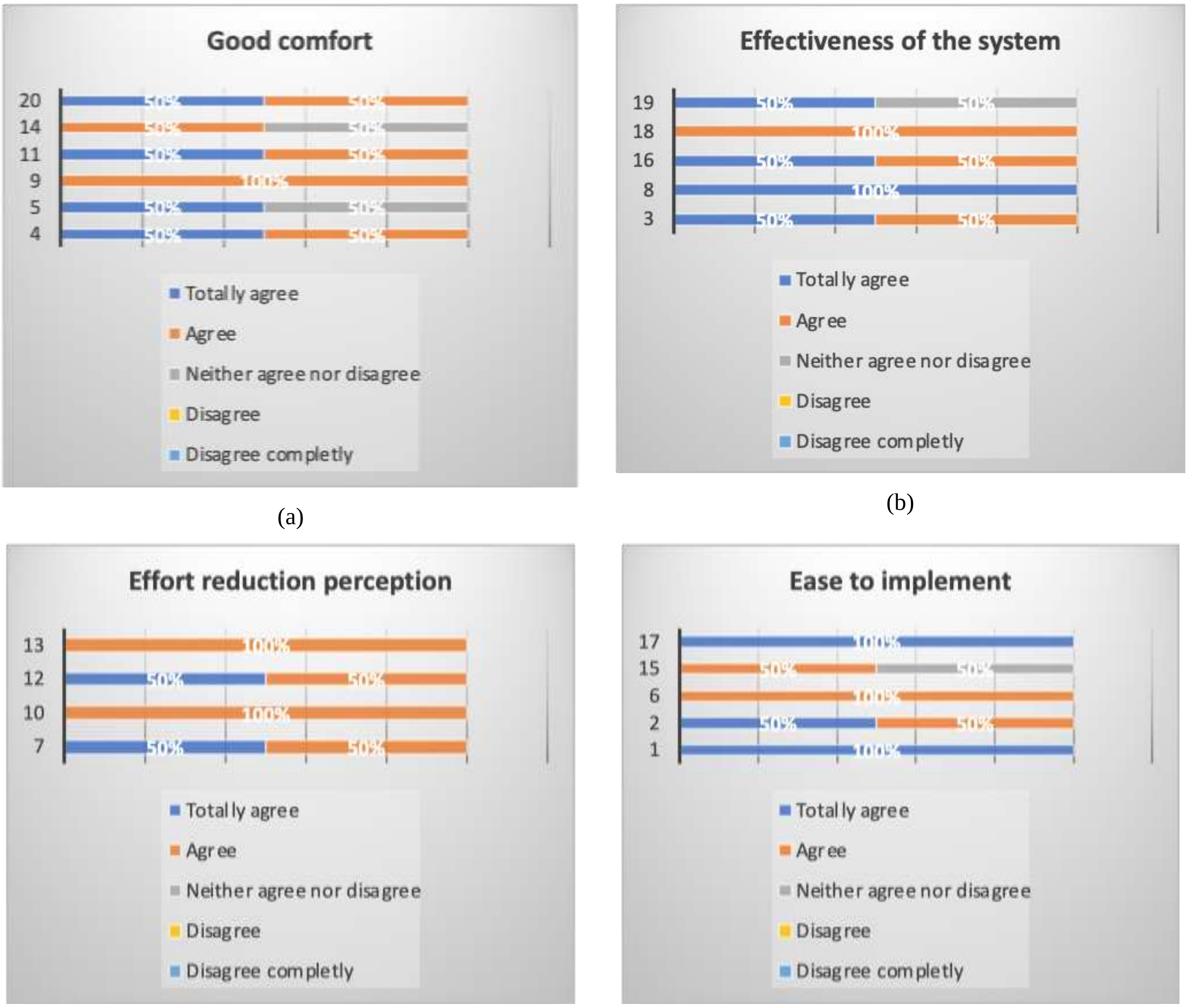


(a) (b)

Figure 11: Mean heart rate for a last 30 seconds lifting task: (a) subject 1; (b) subject 2

### 4.4 Subjective criteria

For both participants, the use of the HAPO is appreciated for the load carrying task only. Results of the survey have been grouped in four categories: “Good comfort”, “Effectiveness of the system”, “Effort reduction perception”, “Ease to implement”.



(a) (b)

(c) (d)

Figure 12: Overall answer of using the HAPO engaged for the load carrying task of both participants, (a) Good comfort, (b) Effectiveness of the system, (c) Effort reduction perception, (d) Ease to implement.

## 5. DISCUSSION

The results vary from one individual to another. Some elements show us that the use of the exoskeleton makes it possible to limit the efforts and constraints, but others refute this tendency. The analysis of the muscular activity was carried out under two different tasks: a static task and a dynamic task.

For the static task, muscle activity varied little, probably because the effects of the HAPO are felt when the stresses are more attenuated. However, subject 2 has a more dominant muscle load when wearing the HAPO, which is probably due to the participant's additional concentration in performing the task, regarding the survey answers.

For the load-carrying task, we note that the lower limbs are not used very much. It would seem that the HAPO does not disturb postural balance, or even very little. This is very relevant because when using an exoskeleton there is often a perceived instability. Subject 1 decreases muscle activity in the arms and back. Subject 1's anterior deltoid "With HAPO disengaged" has an excess value which results from friction with the electrodes during movement amplifying the signal further although it has been filtered.

Subject 2 has an increase in muscular load on the arms and back with the HAPO on which can be explained by amplified movements with the exoskeleton. There is an adaptation time for the device which could influence its use and modify certain expected phenomena. This increase can also result from the coating of an inappropriate size HAPO causing anomalies in the use of the device and thus initiating muscular over-solicitation.

As for the kinematics we can see that subject 1 has a smaller trunk flexion range of motion when wearing the exoskeleton.

During the load-bearing task, the gravitational forces of the trunk and the external loads compress the spine and constitute a risk factor for the development of low back pain.

Exoskeletons can reduce these stresses [9]. Therefore, the angular variation of torso flexion in the sagittal plane have been analyzed.

Subject 1 bends his back less to fetch the load at the same distance when wearing the HAPO. This could be explained by an assistance of the movement of the HAPO which is accompanied by the thighs allowing the spine to bend less and thus limiting the articular constraints of the spine. Subject 1 has a decreased range of motion but a longer movement time with the use of the HAPO according to the studies of Jarassé [12] and Bastide[13]. Thus, there is certainly a smaller range of motion, but the person loses time to complete the task. A consensus should be found between preserving the spine while being productive.

Subject 2 has a greater range of motion. The HAPO is supposed to preserve the spine and in particular the lumbar area. This subject bends lower on average with the HAPO, which can be explained either by a poor use of the HAPO for this individual resulting from a height defect or other, or by a greater concentration of the individual with the HAPO allowing to amplify and exaggerate the movement. In addition, the results show that the time taken to carry out the movement decreases lightly with the use of the exoskeleton for this participant, which would explain why the individual increases the amplitude of these movements.

Greater variability is also observed. We can have an overview of the stability of the movement. This can be disturbed because the body has not had enough time to adapt to the device. The adaptation time is important for our study and is complicated to estimate because it varies from one individual to another.

Heart rate can be an indicator of effort when the task is quite long and requires a lot of effort. An indicator of intensity and effort can be detected when the heart rate is quite high. The task we performed is not representative in this case since these criteria are not met. However, it is nice to observe the average heart rate for each condition to try to detect whether the use of the device allows the subject’s physiological parameters to be modified. The analysis of the heart rate was carried out throughout the different tasks, but the analysis of the last 30 seconds could express a little more of a fatigue phenomenon as the participants were at the end of the repetition. These increases may also be due to the fact that the use of an exoskeleton could modify sensations that the body does not understand and so autonomously, the subject's body will respond to this unknown phenomenon by increasing the heart rate.

The results of the survey of the two participants revealed a good acceptance of the device. The effectiveness and ease of implementation was quickly felt. Improvements have to be performed regarding comfort, particularly at knee level for one of the two participants.

Due to sanitary conditions (COVID19 restrictions) only 2 subjects have been tested. With more participants, we would be able to make statistics and thus analyze several subjects and see what the overall phenomenon of the use of the HAPO leads us.

## 6. LIMITS

The experiment we have developed has limitations and the interpretation of the results must be subject to caution.

The implementation of the HAPO requires a morphological adaptation of the device which is delimited by the red strap. This red strap allows the device to be adjusted so that the joint or spring activation system is aligned with the hip joint.

But this strap also allows the response time of the springs to be adjusted, the tighter the strap, the faster the assistance will be triggered. This parameter therefore depends on each participant and must be standardized so that each subject can be given the same level of assistance. A push button system could address this issue.

Although we want to perform analyses on the spine, allowing us to assess its amplitude and variability, it would be preferable to place the motion capture markers directly on the skin. We are focusing here on the lumbar area where it was not possible to place markers because the exoskeleton has a dorso-lumbar plate which is placed, as its name indicates, at the level of the lumbar vertebrae. It would therefore be necessary to find another way of delimiting the lumbar zone for the analysis without moving this plate, which would give the HAPO user a slight postural support (use of electro-goniometers for example).

It was difficult to analyze the muscular activity of the trapezius muscles (upper fascicle) because the HAPO strap is positioned above the area where the SENIAM base required the exoskeleton to be placed. Some electrodes are placed in areas where there is a high risk of the device rubbing against the sensors, which would induce significant artefacts, although filtering is possible, the signal dispersion is still significant.

An issue also arose regarding the size of the HAPO allocation to participants. The design of the HAPO was based on the distance between the shoulder joint (trochiter) and the hip joint (greater trochanter or acetabulum) to normalize the HAPO sizes. A morphological phenomenon is seen corresponding to an imbalance. Two people corresponding to the HAPO size L measurements do not wear the device in the same way. This element could influence the action of the PAD and provoke other actions than its primary function by not soliciting the same zones. One way would be to try out several HAPOs of different sizes on users to see which device is best suited to them.

Inferential statistics were not possible due to the small number of participants. Indeed, there is no sense in doing a statistical test in our case because there are conditions to be respected and we do not have the statistical power to perform a non-parametric or parametric test.

Thus, if we could perform a statistic test (if we had had at least 3 subjects) we would have used first of all a Kruskall-Wallis test (generalizes the Wilcoxon test) which corresponds to a non-parametric ANOVA. If it were a parametric ANOVA test, it would be a repeated measurements test.

## 7. PERSPECTIVES

This preliminary experiment has made it possible to target the essential parameters to be analyzed in order to determine the benefits or risks that HAPO can bring. The study will continue in the COGITOBIO laboratory, allowing for a larger-scale experiment with more participants and greater precision in the analysis, in particular with the addition of a force platform allowing for the analysis of stability or postural balance. Other conditions will certainly be added to the analysis to ensure that the protocol is carried out correctly. A new device currently being patented will allow comparison with the optoelectronic system for measuring lumbar spine variation and deformation. In order to optimize the user's feeling, a longer adaptation phase will be set up with movements to be carried out to eliminate the effects modifying the neutrality of the movements and the feeling

## 8. CONCLUSION

The analysis method used in this study by coupling motion capture system with EMG and ECG could be used to create an evaluation sheet to accompany the design of exoskeletons.

Due to COVID 19 sanitary conditions, the small number of participants in this preliminary study does not allow to justify the effect of HAPO. There are trends that can be observed by analyzing each participant, but the hypotheses cannot be answered in a meaningful way. The creation of a laboratory validation method to study the effects caused by an exoskeleton to follow up on field tests will be constructed in the same way as the study presented to promote the acceptability of the device in companies.

These analyses will make it possible to validate a device and determine how it can be introduced into companies to limit or prevent occupational diseases, particularly MSDs.

Ergosanté Technology has made it possible to market its physical assistance devices for restraint. However, in order for companies to be interested in these products, it is necessary to confirm that the device works.

Once this study has been completed, it will be necessary to guide and describe the process of functional analysis in the field and to set up a rigorous action plan for the proper insertion of an exoskeleton. Collaboration between companies, preventionists, designers, research institutes and occupational health services now seems necessary in order to improve knowledge of the professional use of these technologies, to integrate the needs of the end user into the development of future generations of exoskeletons and, finally, to build the prevention practices into which these new technologies will be integrated.

## ETHICAL STATEMENT

The authors specify that all subjects were previously informed of the test protocol and gave their consent to participate to the experiments.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Assurance Maladie, “Comprendre les troubles musculo-squeletiques”, Article <https://www.ameli.fr/essonne/assure/sante/themes/tms/comprendre-troubles-musculosquelettiques> (2019)

[2] Luttmann, A., Jäger, M., Griefahn, B., Caffier, G., Liebers, F., [Preventing musculoskeletal disorders in the workplace], World Health Organization, Protecting workers’ health series No 5 (2003).

[3] Assurance Maladie, “Employeurs, faites du bien à votre entreprise, agissez contre le mal de dos”, Dossier de presse, <https://www.ameli.fr/fileadmin/user_upload/documents/DP_Lombalgie-06112018.pdf> (06 November 2018).

[4] Assurance Maladie, “Les TMS : définition et impact”, Article, <https://www.ameli.fr/essonne/entreprise/sante-travail/risques/troubles-musculosquelettiques-tms/tms-definition-impact> (2020)

[5] Arnaudo B, Magaud-Camus I, Sandret N, Coutrot T et al. – “ Exposition aux risques et aux pénibilités du travail de 1994 à 2003. Premiers résultats de l’enquête SUMER 2003. Première Synthèse”. 2004 ; 52.1 : 1-8, (2004)

[6] Theurel, J., & Desbrosses, K. “Occupational exoskeletons: overview of their benefits and limitations in preventing work-related musculoskeletal disorders”. IISE Transactions on Occupational Ergonomics and Human Factors, 7(3-4), 264-280 (2019)

[7] Theurel, J., & Desbrosses, K. “Exosquelettes professionnels : Intérêt et limites pour la prévention des lombalgies et des TMS du membre supérieur”. Archives des Maladies Professionnelles et de l'Environnement, 81(5), 433-434 (2020).

[8] Leardini, A., Biagi, F., Merlo, A., Belvedere, C., & Benedetti, M. G. “Multi-segment trunk kinematics during locomotion and elementary exercises”. Clinical Biomechanics, 26(6), 562-571 (2011).

[9] Näf, M. B., Koopman, A. S., Baltrusch, S., Rodriguez-Guerrero, C., Vanderborght, B., & Lefeber, D. “Passive back support exoskeleton improves range of motion using flexible beams”. Frontiers in Robotics and AI, 5, 72 (2018).

[10] Université Médicale Virtuelle Francophone, “La dépense énergétique”, <http://campus.cerimes.fr/nutrition/enseignement/nutrition_3/site/html/2.html> (2011)

[11] Wioland, L., Debay, L., & Atain-Kouadio, J. J. “Acceptation des exosquelettes par les opérateurs : étude exploratoire”. Références en santé au travail, 157, 45-61 (2019).

[12] Jarrassé, N., Tagliabue, M., Robertson, J. V., Maiza, A., Crocher, V., Roby-Brami, A., & Morel, G. “A methodology to quantify alterations in human upper limb movement during co-manipulation with an exoskeleton”. IEEE Transactions on neural systems and Rehabilitation Engineering, 18(4), 389-397 (2010).

[13] Bastide, S., Vignais, N., Geffard, F., & Berret, B. “Analysis of human-exoskeleton interactions : an elbow flexion/extension case study”. In Congrès de la Société de Biomécanique (2017).