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Comparative Evaluation of Cervical Exoskeletons Using IMUs

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ABSTRACT

Exoskeletons represent a solution to assist workers, therefore have a main role to play for the prevention of musculoskeletal disorders and pain in the neck and shoulders. To achieve this goal, the evaluation of the exoskeletons requires scientific methods and protocols to prove their effectiveness and to make recommendations. Specifically, cervical exoskeletons could be a valuable ergonomic solution to reduce stress on the neck and shoulders. In this randomized crossover design study, 8 participants (3 women) performed dynamic and static head extensions in a sitting position for 3 minutes (followed by a rest period) without neither trunk support nor exoskeleton. The same protocol was then repeated using successively three different models of head/neck exoskeleton available on the market. We evaluated the joint angles of the head movements, the bioelectrical activity of the sternocleidomastoid muscle, the heart rate and the subjective discomfort. Differences were highlighted in terms of comfort, utility, usability, safety coming from both the design logic of the tested solutions and the subjects' morphology. Taken all together, the results of this comparative analysis allowed to better understand the technical and human features to consider for the design of exoskeletons and to build a conceptual, C-K theory based synthesis for the design logic of exoskeletons.

Keywords: Exoskeleton, Evaluation, Ergonomics

INTRODUCTION

Musculoskeletal disorders (MSD) are non-traumatic, work-related pain or symptoms which affect tendons, muscles, ligaments, tissues around the joints or nerves. More specifically, within the scope of the NOMADe project (https://nomadeproject.eu/), La Paglia et al. (2021) defined neuro-musculoskeletal disorders as "a set of dysfunctions and/or affections of progressive or traumatic installation that affect the locomotor system" and appearing within the "framework of complex interactions between the skeletal, muscular, and nervous systems responsible for movement". MSD account for 87% of occupational diseases in France (CNAMTS, 2021) and affect part of the workforce. Many methods and tools are available for assessing MSD risks (Norval, 2019), however it is still a challenge to promote and to implement technical, organizational and human prevention measures to control for these risks. New technologies for physical assistance, such as exoskeletons, offer new possibilities for prevention. An exoskeleton can be defined as a "fully or partially worn device whose purpose is to assist in the execution of the movements, by compensating for the efforts of the individual and/or increasing their physical performance to perform their occupational duty, with the objective of productivity, facilitation of use, and reduction of musculoskeletal disorders" (AFNOR, 2017). Exoskeletons can be classified as passive, semi-active, or active (Crea et al., 2021) depending on the type of assistance provided. While exoskeletons might represent a way to limit MSD, this technology must be considered only after a workstation analysis during which the occupational risks would have been assessed and other preventive measures deemed unfeasible (Kouadio et al., 2018). Numerous studies have focused on the evaluation of different types of assistive devices, such as handling or holding arms up (De Bock et al., 2022). Regarding cervical exoskeletons, only a few articles have really given interest on their potential. To our knowledge, only Garosi et al. (2022) demonstrated (i) a significant decrease in cervical and shoulder discomfort, (ii) a decrease in the muscular activity of the sternocleidomastoid muscles, and (iii) an increase in the muscular activity of the trapezius muscles, while wearing a passive head/neck supporting exoskeleton for overhead work use. Then, the unanswered question is how this information could be used to help for the choice of the best solution within several models or how it could orientate the development of a new exoskeleton.

In the current study, we will compare different cervical exoskeletons to determine the effects of wearing them on joint motions, muscle activity, heart rate and to get the subjective discomfort felt by participants. From these information, we propose a formalization of the exoskeleton concepts from the standpoint of the C-K theory (Hatchuel et al., 2003), a design theory defined as a double expansion process based on both the Concept and the Knowledge spaces.

METHODS

Eight healthy adults (27.4±12.3 years; 1.72±0.09 m, 3 women) voluntarily participated in this study. Three exoskeletons were tested: the Paexo Neck (Ottobock, 2019), the Skelex Neck (Skelex, 2019) and the Moon (HMT, 2021) (Figure 1). These exoskeletons all three consisted in an interface in contact with the base of the skull, and only differ by the way they are attached to the body. The Paexo Neck and the Skelex Neck use a support on the shoulders and the upper back. The whole system is held in place by straps attached to the front of the pants' belt. As for the Moon, a system of strap around the shoulders maintains the device. The Paexo Neck is made by two independent parts which allow to adjust the exoskeleton. The interface of the Moon can also be adjusted with a strap.

For each model of exoskeleton, the participants performed movements of cervical extension for a 3-minute dynamic test and a 3-minute static test. Both tests were performed while the subject was seated on a chair. The same tests were also performed without exoskeleton to provide baseline outcomes. Trials were randomized for both the model of exoskeleton and the type of activity (static or dynamic). Between two trials, the subjects had a 3-minute

Figure 1: Paexo Neck, Skelex Neck and Moon exoskeletons

rest phase. No specific information was given neither about the range nor the frequency of the flexion extension movements. A Motion CAPTIV solution (TEA, France) was used to get synchronized signals from the wireless inertial sensors, the surface electromyographic sensors (sEMG) , a Polar OH1 optical heart rate sensor (Hettiarachchi et al., 2019) and videos captured by a webcam (Peeters et al., 2019).

We evaluated (i) the average physiological cost, through the changes in the heart rate expressed as a relative cardiac cost (RCC) (Boudet et al., 2018), (ii) the range of motion of the head and spine movements, and (iii) the sEMG activity of the sternocleidomastoid muscle. The global and local perceptions of the task intensity have also been assessed using the Borg scales (Meyer, 2014) : the Rated Perceived Exertion (RPE) Scale for the physiological level of activity, as well as CR10 Scale for the cervical and lumbar spine. Wilcoxon tests for paired samples were run and analyzed with $p<0.05$ as the significant level.

RESULTS

The heart rate mean demonstrated only a decrease when using the Moon exoskeleton (69±12 beats/min) in comparison to a static test performed without exoskeleton (71±11 beats/min) ($p = 0.018$).

The RPE mean value was lower with the Moon than with the Paexo ($p = 0.028$).

When considering the subjective feelings perceived by the participants, CR10 values were decreased with the Moon and the Skelex models compared to a situation without exoskeleton (Figure 2).

Compared to the trial without exoskeleton, the static neck extension has been reduced in trials implying the use of a Paexo or a Skelex exoskeleton (Figure 4). In a dynamic condition, the neck extension was found to be reduced with a Moon or a Skelex exoskeleton (Figure 3).

The figure 5 presents, for a participant, the mean and standard deviation for the extension cycle recorded during trials without an exoskeleton, with the Moon and with the Skelex.

DISCUSSION

Exoskeletons that provide support for the head and assistance in extending the head also cause physical strain. The subjective evaluation of the support

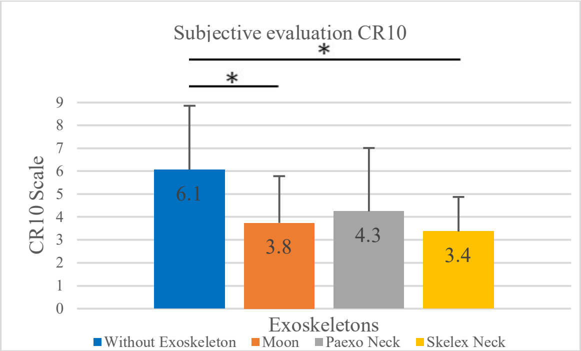

Figure 2: Subjective evaluation CR10. Significant differences are indicated by an asterisk.

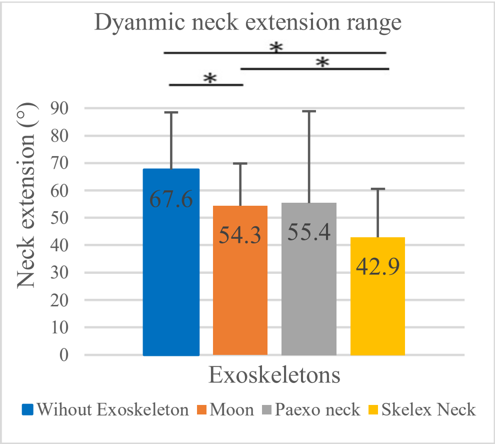

Figure 3: Dynamic neck extension range. Significant differences are indicated by an asterisk.

for static activity was convincing. However, the results for electromyographic analysis were not significant.

Only the Moon allowed to keep an overall amplitude close to the situation without exoskeleton. This can be explained by the larger arc of rotation of the system. The Paexo Neck and the Skelex Neck offer more flexibility in the part which supports the interface, and this contributes to the assistance.

The design logic of these exoskeletons is different. The Paexo Neck with an adjustable interface potentially reduces the arc of the assistance. The Skelex Neck, with a single part, offers a more consistent arc and finer flexibility. Finally, the Moon, with a much larger arc, offers even finer assist sensitivity. The Moon, unlike the two other exoskeletons, has a more comfortable interface due to its material. The level of assistance is not adjustable for these exoskeletons. Only the positioning and restraint settings can be adapted to the user's morphology. Pant straps for the Paexo Neck and the Skelex Neck need to be adjusted to the posture. Shoulder straps for the Moon can represent a nuisance over time. Opinions differed through the subjects but what

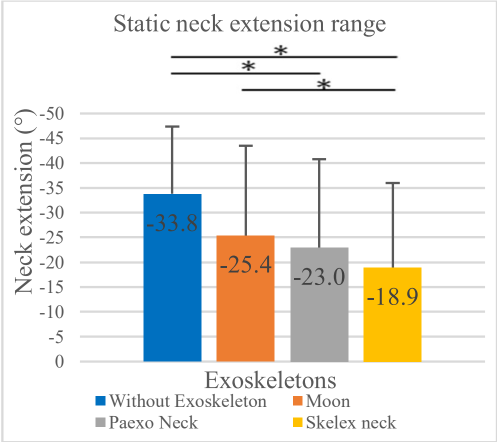

Figure 4: Static neck extension range. Significant differences are indicated by an asterisk.

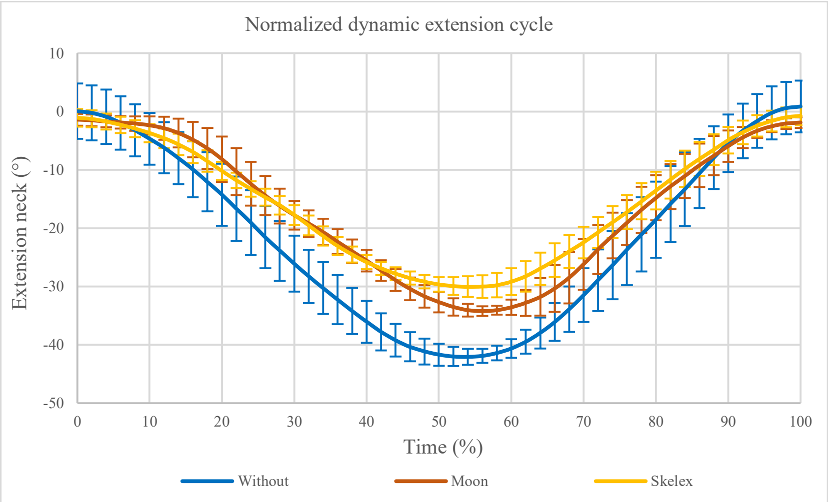

Figure 5: Neck extension expressed as a percentage of the cycle.

emerges is that the Moon is very comfortable in static, is uncomfortable during movement. It could related to excessive assistance, while the Skelex Neck having a certain flexibility of the interface the base can move away but rises too high. The Paexo Neck is more compact and allows adjustment to the morphology.

From these results, a C-K theory conceptualization can be made. The C-K theory is an innovative design approach proposing an asymmetric structure (Hatchuel et al., 2003) of the C (Concept) and K (Knowledge) spaces. Innovative design methods derived from C-K allow for a continuous dialogue between C and K spaces. This makes it possible to reason in the known and the unknown and, starting from an initial undecidable concept, to propose decidable concepts. The space C shows a partition of Concepts. The space K

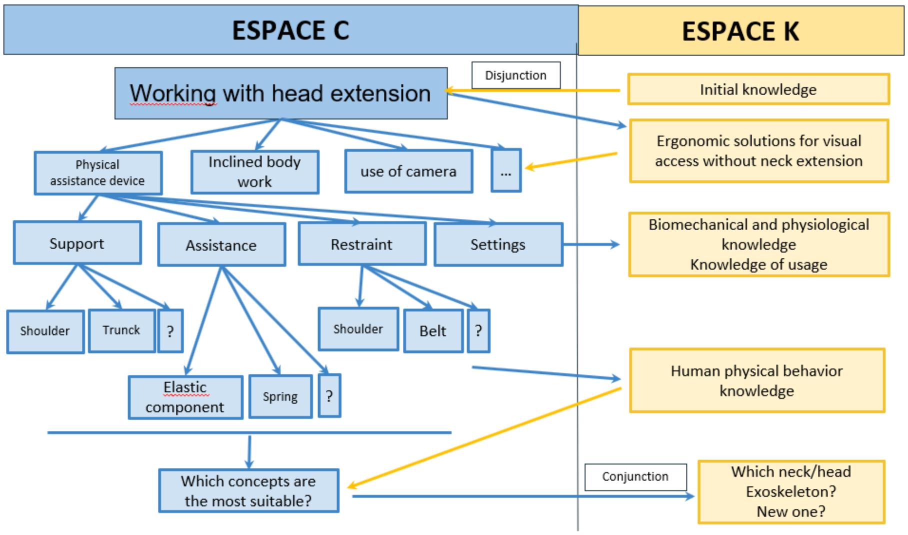

Figure 6: The logic of cervical exoskeletons according to a C-K conception

shows knowledges which contribute to define new concepts. By this way, new research questions can arise, and new products can be designed (Figure 6).

CONCLUSION

This intervention is part of a broader evaluation program with the ambition of proposing a study protocol that will allow to compare exoskeletons providing the same type of assistance and to evaluate the combination of several exoskeletons during a single task.

Considering the results of this study, some parameters will have, to be considered differently (frequency of the movements, duration of the phases) for the next experiments with new generations of exoskeletons.

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REFERENCES

AFNOR (2017) 'AC Z68-800 Dispositifs d'assistance physique à contention de type exosquelettes robotisés ou non. Outils et repères méthodologiques pour l'évaluation de l'interaction humain-dispositif'. Agence Française de NORmalisation.

Boudet, G., Chamoux, A. and Dutheil, F. (2018) 'L'astreinte cardiaque est individuelle et doit être évaluée', *Archives des Maladies Professionnelles et de l'Environnement*, 79(3), p. 334. doi:10.1016/j.admp.2018.03.273.

CNAMTS (2021) *Rapport annuel 2020 de l'Assurance Maladie - Risques professionnels Éléments statistiques et financiers*. Caisse Nationale d'Assurance Maladie des Travailleurs Salariés

Crea, S. *et al.* (2021) 'Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces', *Wearable Technologies*, 2. doi:10.1017/wtc.2021.11.

De Bock, S. *et al.* (2022) 'Benchmarking occupational exoskeletons: An evidence mapping systematic review', *Applied Ergonomics*, 98, p. 103582. doi:10.1016/j.apergo.2021.103582.

Garosi, E. *et al.* (2022) 'Design and ergonomic assessment of a passive head/neck supporting exoskeleton for overhead work use', *Applied Ergonomics*, 101, p. 103699. doi:10.1016/j.apergo.2022.103699.

Hatchuel, A. and Weil, B. (2003) 'A new approach of innovative design: an introduction to C-K Theory', p. 15.

Hettiarachchi, I.T. *et al.* (2019) 'Validation of Polar OH1 optical heart rate sensor for moderate and high intensity physical activities', *PLOS ONE*. Edited by D. Boullosa, 14(5), p. e0217288. doi:10.1371/journal.pone.0217288.

HMT (2021) 'Moon'. https://www.hmt-france.com/fr/ourExoskeletons/moon consulted 2022-05-05

Kouadio, J.-J.A., Kerangueven, L. and Turpin-Legendre, E. (2018) 'Acquisition et intégration d'un exosquelette en entreprise', p. 36.

La Paglia, V. and Telliez, F. (2021) 'Les facteurs de risque en matière de troubles neuro-musculo-squelettiques: vers une définition socio-psychobiologique'.

Meyer, J.-P. (2014) 'Évaluation subjective de la charge de travail. Utilisation des échelles de Borg', p. 18.

Norval, M. (2019) *Les outils simples d'évaluation du risque d'apparition des troubles musculo-squelettiques (TMS) : quelle intégration de la marge de manoeuvre situationnelle (MMS) dans le cadre du repérage des situations à risques ?* . Thèse de doctorat Université Angers.

Ottobock (2019) 'Paexo neck'. https://paexo.com/paexo-neck/?lang=en consulted 2022-05-05

Peeters, T. *et al.* (2019) 'Full Body Three Dimensional Joint Angles Validation Using TEA Ergo Inertial Measurement Units', in Ahram, T., Karwowski, W., and Taiar, R. (eds) *Human Systems Engineering and Design*. Cham: Springer International Publishing, pp. 879–884. doi:10.1007/978-3-030-02053-8_133.

Skelex (2019) 'Skelex neck'. https://www.skelex.com/register-skelex-neck-support/ consulted 2022-05-05