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Biomechanical effects of using a passive upper-limb exoskeleton to assist firefighters during vehicle extrication maneuver

P. Maurice^{a*}, S. Lemonnier^b, N. Kohili^c, L. Cavagnac^b, G. Mornieux^c

^a Université de Lorraine, CNRS, Inria, Loria, F-54000 Nancy, France; ^b Université de Lorraine, PerSEUs, F-57000 Metz, France; ^c Université de Lorraine, DevAH, Faculty of Sport Sciences, F-54000 Nancy, France.

1. Introduction

Firefighters' work involves numerous strenuous tasks, which often lead to the development of musculoskeletal disorders (MSDs) (Kodom-Wiredu 2019; Nazari et al. 2020; Frost et al. 2015). Among these tasks, vehicle extrication is particularly demanding because it requires the manipulation of heavy cutting tools (20 to 30 kg) in constrained and non-ergonomic postures. While adequate physical training is of utmost importance and can help reduce MSDs risk, it is not sufficient alone, especially with the current aging of the workforce.

In industry, occupational exoskeletons have been proposed as a potential solution to alleviate the physical load on workers, and thereby reduce MSDs risk (De Looze et al. 2016; Theurel & Desbrosses 2019). While exoskeletons are envisioned as a promising solution for firefighters as well (Taborri et al. 2021), their benefit is strongly task-dependent. So far, exoskeletons for firefighters have mainly been developed as whole-body powered devices for strength enhancement in load carrying tasks (Osipov 2019). However, the use of lighter and less cumbersome occupational exoskeletons with MSDs reduction in mind has, to the best of our knowledge, not been studied. This work therefore investigates the biomechanical effects of using a passive upper-limb exoskeleton during the vehicle extrication maneuver.

2. Methods

2.1 Participants and Protocol

Twelve male firefighters (7 professionals and 5 volunteers; age: 31 ± 9 yrs; experience: 11 ± 9 yrs; height: 175 ± 5 cm; mass 73 ± 6 kg) performed a vehicle extrication maneuver (Fig. 1), both with (WE) and without (NE) the exoskeleton. The maneuver consisted in a timed sequence of three subtasks performed at different heights on the vehicle, with two different cutting tools (about 22 kg each), for a total duration of 3 min. The two conditions were performed in random order, with a 15 min break in between. The study was approved by INRIA's ethical

committee COERLE, and was conducted in accordance to the Declaration of Helsinki.



Figure 1: Firefighters equipped with the MATE exoskeleton performing a vehicle extrication maneuver.

2.2 Instrumentation

The participants were equipped with the Xsens MVN Link inertial motion capture system (capture rate 240 Hz) to record whole-body kinematics. Fourteen Delsys Trigno Snap-Lead EMG sensors were placed according to the Seniam recommendations bilaterally on the erector spinae (ES), latissimus dorsi (LD), anterior deltoid (AD), upper trapezius (TR), biceps brachii (BB), triceps brachii (TB) and brachioradialis (BR) to record back, shoulder and arm muscle activity (capture rate 1926 Hz). Finally, a Garmin Forerunner 345 sensor was placed on the participants' chest to monitor heart rate (capture rate 1 Hz).

At the end of each condition, participants answered a Borg CR10 questionnaire to evaluate the effort perceived in five body areas: shoulders, upper-arms, forearms, abdominal and lumbar (Borg 1998).

2.3 Exoskeleton

The exoskeleton used in this study is the MATE-XT (Comau, Torino, Italy). It is a lightweight (3 kg) passive upper-limb exoskeleton designed to provide shoulder support in tasks involving arm elevation (Pacifico et al. 2020). The MATE was selected as a test candidate following a preliminary study of the non-assisted extrication maneuver, in which the shoulder was identified as the primary joint to assist. Among commercially available exoskeletons for shoulder support, the MATE was deemed a good compromise between the level of assistance provided and the device compactness imposed by the task.

In the present study, the firefighters wore the exoskeleton over their work clothes, and the highest level of assistance was always used (6 kg per arm). Before starting the task, participants could move around and manipulate the cutting tools during a few minutes to familiarize with the exoskeleton.

2.4 Data analysis

The following dependent variables were analyzed: average cardiac cost (current minus rest heart rate) over the last 3 sec of the task; root mean square value of the filtered EMG signal over the whole task for

each of the 14 recorded muscles; percentage of time spent in the different zones inspired from the RULA ergonomics assessment method (McAtamney & Corlett 2004) for the back (<20 deg; 20-60 deg; >60 deg), left arm and right arm (<45 deg; 45-90 deg; >90 deg) flexion/extension; perceived effort (Borg score) for each of the five body areas.

Due to the non-normality of the data, Wilcoxon signed-rank tests were conducted for all dependent variables to evaluate the effect of the exoskeleton. A significance level of 5% was used.

3. Results

Kinematics: When using the exoskeleton, participants spent more time with their left arm in the 45-90 deg elevation zone and less in the 0-45 deg zone, compared to without it (+7% in average). There was no significant difference for the right arm or back.

Muscle activity: The use of the exoskeleton caused a significant increase in the activity of the right BB (by 10% in average). All other muscles were unaffected. Even the activity of the left shoulder muscles remained similar, despite more time spent with the arm elevated when using the exoskeleton.

Heart rate: The cardiac cost was not significantly affected by the use of the exoskeleton.

Perceived effort: A significant reduction was observed for the shoulder (by 22% in average), upper-arm (by 22% in average), and forearm (by 26% in average) areas when using the exoskeleton (Fig. 2). For the abdominal and lumbar areas, the exoskeleton also reduced the perceived effort, but not significantly.

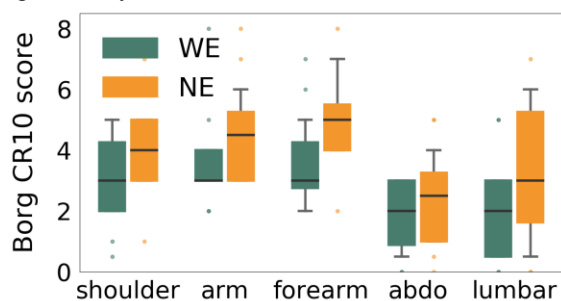


Figure 2: Distribution across participants of the Borg CR10 scores of the 5 body areas, with and without the exoskeleton.

4. Discussion and Conclusion

This study suggests that there is no physiological benefit in using the MATE exoskeleton for the extrication maneuver, except possibly a mild assistive effect on the left shoulder (similar muscle activity despite higher arm elevation). This may be due to the low arm elevation angle adopted by most participants (<45 deg during most of the task), where the MATE provides only limited assistance, especially compared to the weight of the cutting tools. Interestingly

though, participants reported a reduction of perceived effort with the exoskeleton, which suggests either a placebo effect of the device, or biomechanical changes that are too small to be detected with the proposed methodology, given the large task's degree of freedom.

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*Corresponding author.
 pauline.maurice@loria.fr

Email: