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Work performance in industry: The impact of mental fatigue and a passive back exoskeleton on work efficiency

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ABSTRACT

Mental fatigue (MF) is likely to occur in the industrial working population. However, the link between MF and industrial work performance has not been investigated, nor how this interacts with a passive lower back exoskeleton used during industrial work. Therefore, to elucidate its potential effect(s), this study investigated the accuracy of work performance and movement duration through a dual task paradigm and compared results between mentally fatigued volunteers and controls, with and without the exoskeleton. No main effects of MF and the exoskeleton were found. However, when mentally fatigued and wearing the exoskeleton, movement duration significantly increased compared to the baseline condition ($\beta_{MF:Exo} = 0.17$, $p = .02$, $\omega^2 = .03$), suggesting an important interaction between the exoskeleton and one's psychobiological state. Importantly, presented data indicate a negative effect on production efficiency through increased performance time. Further research into the cognitive aspects of industrial work performance and human-exoskeleton interaction is therefore warranted.

1. Introduction

Pursuing maximal efficiency of production processes by continuous optimization is crucial for competitive manufacturing companies. Hence, innovative technologies and automation, e.g., collaborative robots, augmented or virtual reality, and smart production systems, are increasingly implemented in supply chains (Kolus et al., 2016). Currently, these technologies are often dependent on the (co-)performance of human operators (Kolus et al., 2016). This implicates that human factors can affect overall productivity, e.g., fatigue or boredom hampering worker's ability to maintain a competitive cycle time versus work motivation and sufficient rest enhancing a qualitative production process (Kolus et al., 2016). Therefore, identifying and addressing faulty human factors with regard to work performance is crucial for safeguarding and further enhancing productivity.

One of the most investigated human factor in relation to industrial work performance is physical fatigue. However, mental fatigue (MF), defined as a psychobiological state caused by prolonged periods of demanding cognitive activity (Van Cutsem et al., 2017) should not be disregarded from this context. Performing precision work, adhering to strict time constraints, and remaining alert during an entire work shift in an often noisy distracting environment are also essential human factor requirements for the performance of industrial work and could therefore induce MF. Currently, the amount of studies investigating the impact of MF on work performance during manual material handling tasks in manufacturing is limited. Although scarce, Hopko et al. (2021) reported a decrease in performance speed during a polishing task when mentally fatigued. Moreover, links between MF and decreased productivity

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already have been found in tertiary sectors like healthcare (McCormick et al., 2012), transportation (Guo et al., 2018) and in administration (De Jong, Bonvanie, Jolij and Lorist, 2020). These decrements can be explained by the link between MF and impaired cognitive and motor skills, i.e. decrease in attention, decrease in accuracy of movement, increase in reaction time (Boksem et al., 2005; van der Linden and Eling, 2006). Since efficiency is a crucial requirement for conducting work in an industrial environment, one can assume that changes in aforementioned skills indeed negatively impact the production process. However, this has never been researched during manufacturing tasks, highlighting the necessity for further exploring MF and its, hypothesised, negative effect on work performance within secondary industrial sectors.

Given the increasing body of research on physical fatigue, we can expect the development of various promising technologies to limit its onset, thereby preventing associated risks, including work-related musculoskeletal disorders. Industrial exoskeletons, are a prime example. Although designed to prevent musculoskeletal injuries, these devices could affect industrial work performance since energetic cost (Baltrusch et al., 2020; Schmalz et al., 2019) and a delay in the onset of muscle fatigue (De Bock et al., 2022; Lamers et al., 2020; Schmalz et al., 2019; Yin et al., 2019) might increase physical performance. Additionally, increased cognitive demands, associated with the human exoskeleton interaction could influence work efficiency if employees do not have sufficient cognitive resources available to correctly operate the exoskeleton when conducting their work tasks (Zhu et al., 2021). A well-investigated example of an industrial exoskeleton is the Laevo V2.56 passive back exoskeleton (Laevo B.V., Delft, Netherlands) (Baltrusch et al., 2018; Bosch et al., 2016; Luger et al., 2021). Research indicates that the Laevo exoskeleton successfully reduces muscle activity of the trunk extensors as well as discomfort in the low back region (Bosch et al., 2016; Luger et al., 2021). Furthermore, an increased endurance time due to the support (Bosch et al., 2016) and good usability of the device (Luger et al., 2021) were described. However, inconsistencies regarding the influence of the Laevo exoskeleton on work performance complicates to draw strong conclusions from previous research. Furthermore, to the best of our knowledge, only one study investigated the cognitive component of the human-exoskeleton interaction with this specific type (Zhu et al. (2021) and reported an increased neurocognitive demand when using the Laevo exoskeleton. Nonetheless, ensuring a limited strain on users cognitive resources while optimizing work performance is crucial to safeguard the user from abovementioned decreases in cognitive and motor skills due to MF as well as to secure the efficiency of the production process from delays or errors (Zhu et al., 2021). Acknowledging that industrial workers are at risk for developing mental fatigue, and that working with an exoskeleton may increase the workers' cognitive load, it is important to consider the extent to which such a combination is detrimental to the production process. This implies the need for further research to understand the relation between the Laevo exoskeleton and MF and to gain more insight in the changes in users work performance associated with the industrial exoskeleton as well as with MF.

Until now, no studies have investigated the relationship between MF, the Laevo exoskeleton and work performance. Hence, it is challenging to anticipate the implications on production processes. Considering that the implementation of exoskeletons in industrial sectors is expected to increase over time, it is crucial to comprehend its contribution to MF as well as its functionality when the wearer is mentally fatigued. Therefore, the first aim of this research paper was to assess the impact of MF and the Laevo exoskeleton on work performance. The second aim was to assess whether the Laevo exoskeleton would contribute to MF. We hypothesised that (i) MF would negatively affect work performance, (ii) wearing the exoskeleton would positively influence work performance, (iii) the exoskeleton would contribute to MF, and (iv) MF would counteract the added value of the exoskeleton regarding work performance.

2. Material and methods

2.1. Subjects

Six healthy males and five healthy females (mean 23.6 years ± SD 2.8 years) participated in this randomised, counterbalanced cross-over study. None of the participants suffered from any known somatic or mental disorders. Volunteers were excluded in all cases where medical conditions or histories could compromise a safe completion of the experiment.

All participants received information about the study and signed a consent document prior to participation. The experimental protocol (B. U.N. 1432020000271) was approved by the Medical Ethics Commission of the Vrije Universiteit Brussel and University Hospital Brussel and was registered at ClinicalTrials.gov (Identifier: NCT04721392).

2.2. Experimental protocol

For each participant, the experiment consisted of 4 experimental sessions, separated by an interval of at least 2 days to ensure full recovery. Each session started with a dual task, consisting of a physical and a cognitive task (cf. 2.2.1 Dual task). Work performance was assessed during this dual task and included the following parameters: accuracy cognitive task, accuracy physical task and movement duration. Questionnaires regarding workload (NASA-TLX), MF (M-VAS) and boredom (B-VAS) were completed after each performance. The same dual task with the same outcome parameters was then repeated after 60 min in one of 4 conditions defined by the intervention or control task for MF. MF was induced by means of an individualised Stroop task (cf. 2.2.2 Mentally fatiguing task). A neutral documentary (~60 min) was watched as a control condition for the MF-intervention (Fig. 1). Depending on the experimental condition, both dual tasks were performed with or without an exoskeleton (Exo) (cf. 2.2.3 Passive back-support exoskeleton). The order of the conditions (MF-Exo, MF-NoExo, NoMF-Exo, NoMF-NoExo) was determined randomly by a web-based computer program. Participants were always scheduled on a similar time of day and were instructed to keep circadian habits fixed prior to each experimental trial. To minimise possible learning effects, the experiment was preceded by an extensive familiarisation period with, on average, three days between the last familiarisation trial and first experimental trial.

During the familiarisation period, participants performed a dual task twice a day for two consecutive days. After each dual task performance, the exoskeleton was fitted and participants performed different exercises (e.g. stooping, squatting, walking), in accordance with the Laevo V2.56 exoskeleton manual (Laevo B.V., Delft, Netherlands) to get familiar with the device. During the last day of the familiarisation period, participants completed an experimental trial with the exoskeleton to get acquainted with the experimental procedures and measurement devices. The individual stimulus presentation time of the Stroop task (cf. 2.2.2 Mentally fatiguing task) was also determined on this day.

2.2.1. Dual task

The dual task consisted of a physical (repetitive lifting-lowering) and a cognitive (calculation) task. A 5 kg box (L = 30 cm, W = 20 cm, H = 17 cm) with two hand-holes was transferred by the participant between ground level and pelvic level for 15 min. At both levels, tape delineated the precise location of the box. At ground level, the tape was placed to centre the box 50 cm in front of the ankle joint to ensure a comfortable lifting-lowering movement in accordance with the NIOSH guidelines (Waters et al., 1994; Waters et al., 1993). At pelvic level, the platform was set to the height of the spina iliaca anterior superior and was placed 80 cm in front of the ankle joint in order to mimic a more awkward lifting position. At the start of every trial, the box was positioned on the pelvic platform. Every 6 s, the initiation of each movement, i.e., relocating the box to another level, was cued by a metronome. Participants

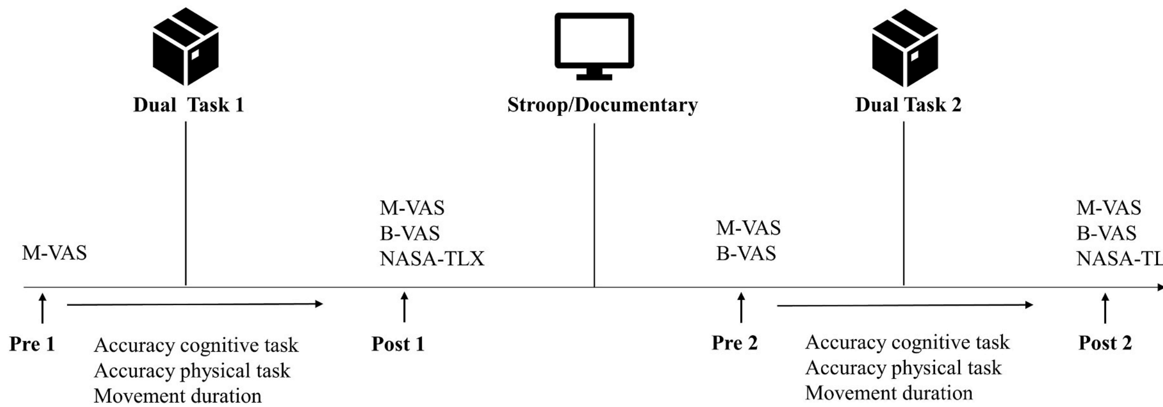

Fig. 1. Overview of experimental design.

were asked to transfer the box using a semi-squat lift (a posture incorporating both squat and stoop lift characteristics, defined by moderate knee flexion and trunk inclination) since this lifting technique corresponds most closely to the self-selected technique (Straker, 2003). In between movements, participants were asked to stand in an upright position. The mass of the box was selected in accordance with the lifting and lowering guideline weights published by Pheasant and Haslegrave (2006) (Fig. 2).

During the lifting and lowering task, participants conducted a cognitive task. This included a calculation task in which they had to continuously subtract seven from a randomly selected number between 900 and 950 as fast as possible (modification of Serial sevens). The given starting number was changed for each trial to minimise learning effects. Participants were not informed about calculation errors. The participants were instructed to prioritize accuracy of the box placement rather than the calculation task to improve reliability of the dual task (Plummer and Eskes, 2015).

2.2.2. *Mentally fatiguing task: The stroop task*

To induce mental fatigue, a Stroop task (~60 min, 4 blocks, 481 stimuli) was customised for each participant by means of an individualised stimulus presentation time. This indicates the duration of each word displayed on the screen. In this task, the words “blue”, “green”, “yellow”, and “red” are one by one digitally displayed in an incongruent colour e.g., the word green displayed in the colour yellow (Appendix C). Participants were instructed to indicate the colour display of the word, rather than the semantic meaning of the word. Displaying a word in red was an exception and, in this case, participants had to indicate the semantic meaning of the word. The computer randomly selected the words and the colour in which they were presented (100% incongruent), each word-colour combination was equally prevalent. Each presented word was displayed in a 34-point font and participants were asked to respond as quickly and accurately as possible. The stimulus presentation time of the Stroop task was priorly customised for each participant in the familiarisation trial. Here, participants first performed 3 blocks with each 36 stimuli with an STP of 1500 ms to get acquainted with the task. When the accuracy was higher than 85%, the stimulus presentation time was decreased in following order: 1200, 1100, 1000, 900, 800, 700, and 600 ms to gradually increase the difficulty level of the Stroop task. If 85% was not reached, participants were asked to repeat the block until either three consecutive or a total of five fails occurred.

2.2.3. *Passive back-support exoskeleton*

In this experiment, the passive Laevo V2.56 exoskeleton (Laevo B.V., Delft, Netherlands) was used. This exoskeleton has a weight of 2.8 kg and provides support for trunk flexion and hip extension during forward bending and lifting. The chest pad, hip belt, and leg pads at the anterior side of the thighs are the main components. Semi-rigid bars on both sides of the exoskeleton connect the chest pad and hip belt. These are available in different sizes in order to adjust for different body types. The smart joints (torque generating system) are located at the hip centre and support trunk flexion and hip extension with their spring like characteristics.

2.3. *Instrumentation and measurements*

For the cognitive task (i.e., the calculation task), calculation errors, were logged in an Excel database and accuracy percentages were

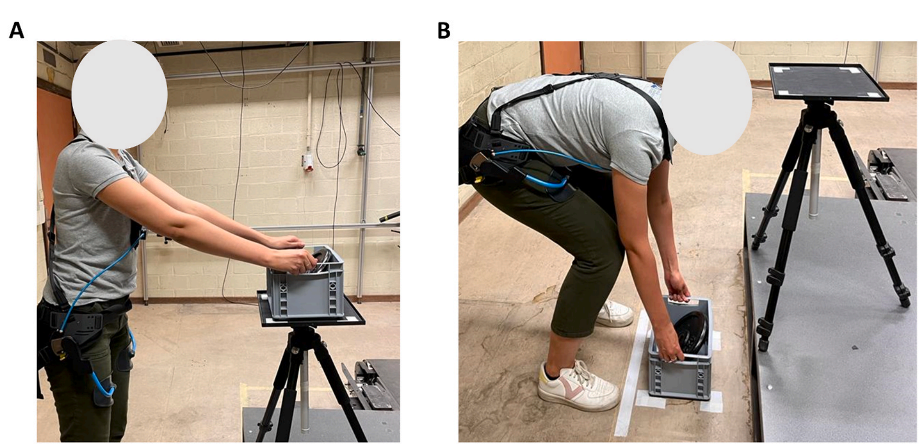

Fig. 2. Dual task performance. Participants iteratively repositioned a 5 kg box between a predefined area on the pelvic platform (A) and ground (B) using a semi-squat movement. A calculation task was simultaneously performed.

calculated for the correct answers, i.e. the calculation score. Regarding the accuracy of the physical task, a Vicon system with 10 infrared high-speed Vero cameras (100 Hz, Vicon, Oxford Metric Ltd., Oxford, UK) was used to capture the movements of the box. Reflective Vicon markers (d = 14 mm) were placed on each corner of the box and platforms to calculate accuracy of placement and the duration of the lifting and lowering movement.

To assess MF and boredom, visual analogue scales were used (M-VAS and B-VAS, respectively). Both VAS scales consisted of a 10-cm line which were labelled at one end with ‘not at all mentally fatigued’ or ‘not at all boring’ and at the other end with ‘extremely mentally fatigued’ or ‘extremely boring’ (Smith et al., 2019). Participants were instructed to indicate, with a vertical line on the scale, their level of MF and boredom. Scores could range between zero and ten. Workload was assessed with the NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988) and scores could range from zero (= very low) to 100 (= very high). The M-VAS was administrated pre and post each dual task as well as after the Stroop task; the B-VAS and NASA-TLX were only completed after the performance of each dual task.

2.4. Data-analysis

Nexus 2.11.0 (Vicon, Oxford Metric Ltd., UK) was used for data cleaning where a cyclic gap filling method was applied for reconstructing missing marker data in accordance with the recommendations of Vicon Nexus (Vicon Motion Systems Ltd). This software was also used for exporting the trajectories of the Vicon markers that were attached to the box and both platforms. MATLAB scripts (R20201a, The MathWorks Inc., USA) were then constructed to process these trajectories and to obtain (i) the duration of each lift and lower movement according to the position of the box and (ii) the percentage of overlap between the box and both platforms during each movement.

The sequence of each (i) lifting-lowering movement, and (ii) box placement during the dual task were segmented into 3-min long fragments to portray an overview of duration and accuracy changes throughout the dual tasks. However, since all segments were strongly correlated (duration: $r \geq 088$; box placement: $r \geq 0.99$), one overall mean score for duration and box placement accuracy was calculated per dual task. Due to recording problems, data of two participants were excluded for the analysis of the box accuracy and movement duration.

2.5. Statistics

Multilevel regression models (MLM) were used to investigate the influence of and the interaction between MF and the exoskeleton, hereby accounting for the nesting of time points within participants. Six different MLMs were constructed, one for each outcome. The continuous second-level predictor “age” was grand-mean centered following the advice of Enders and Tofighi (2007). All models control for a potential effect of age and sex. An alpha-error of 5% was considered as a valid cut-off for significance testing.

Due to the small sample size and the large number of parameters, a step-wise, bottom-up model building approach was adopted following the approach documented by Hox et al. (2018). At each step, the parameter estimates and corresponding standard errors were inspected to see which parameters were significant, and how much residual error was left at the different levels. Non-significant variables were removed from the model and a model comparison using the chi-square difference test was performed to formally test if this reduced model did not significantly differ from the full model at each step. Next, the improvement of the selected model at each step was also tested by computing the difference of the deviance of that model and the final model from the previous step by means of a chi-square difference test. Finally, the intraclass-correlation coefficient (ICC) and Pseudo-R^2 of the fixed effects and total model were calculated for each step.

In particular, the following models were fitted: First, an intercept-only model (i.e., model without explanatory variable; M_0) was fitted. This model served as a benchmark value of the deviance (i.e., measure of the degree of misfit of the model (Hox et al., 2018). In a second model, all first-level explanatory variables (MF, Exo, M-VAS, B-VAS, NASA-TLX; depending on the outcome variable) were included as fixed effects (M_1). Third, all second-level explanatory variables (Age and Sex) were included to examine whether these explain between-group variation in the dependent variable (M_2). In a fourth step, the slopes of the first-level variable were assessed to have a significant variance component between groups (M_3). This testing for random slope variation was done on a variable-by-variable basis. In a final step, cross-level interactions were included between second-level explanatory variables and the individual-level explanatory variables that had significant slope variation in the previous model (M_4).

Finally, we checked whether the residuals of the model were normally distributed at both levels by means of visual inspections (Appendix D). A check for homoscedasticity was performed on the final models by comparing residuals to the fitted items. In addition, QQ-plots were constructed for both the residuals and random effects. As a final step of the modelling process, variance inflation factors of every variable in the model were inspected for multicollinearity (cut-off value of 5). All analyses were performed in R (R Core Team, 2021). The lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) packages were used to obtain the MLMs, the ggplot2 package was used for the graphics (Wickham, 2016). Since this paper primarily focussed on MF and the exoskeleton, effects of control variables (e.g. sex and age), are discussed to a lesser extent. Detailed descriptions of the MLMs and the dummy coded variables used in the models can be found in Appendix A and B.

3. Results

3.1. Primary outcome measures

3.1.1. Cognitive task: calculation task

No significant association was found between the calculation score and wearing an exoskeleton (M_1: $\widehat{\beta_{\text{Exo}}} = 0.23, p = .18, \omega^2 = .01$) nor between MF and the calculation score (M_1: $\widehat{\beta_{\text{MF}}} = 0.11, p = .75, \omega^2 < -.001$). Also, no significant difference was observed between obtained calculation scores of dual tasks 1 and 2 (M_1: $\widehat{\beta_{\text{Task}}} = 0.44, p = .20, \omega^2 < -.001$) (Appendix A, Table A.1).

3.1.2. Physical task: Movement duration

Task 1 was used as reference category. Here, assuming all other variables constant, movement duration was not affected by wearing the exoskeleton nor by MF in task 1 (M_4: $\widehat{\beta_{Exo}} = 0.11$, $p = .07$, $\omega^2 = .06$; $\widehat{\beta_{MF}} = 0.02$, $p = .85$, $\omega^2 = -.07$). However, in the mentally fatigued group, the exoskeleton significantly increased movement duration (M_4: $\widehat{\beta_{MF:Exo}} = 0.17, p = .02, \omega^2 = .03$) (Fig. 3). Furthermore, a significant decrease in movement duration of dual task 2 was found when wearing the exoskeleton as compared to not working with the exoskeleton (M_4: $\widehat{\beta_{Exo:task2}} = -0.18, p = .01, \omega^2 = .04$). Importantly, movement duration is dependent of age for females, further details can be found in Appendix A, table A.2. The slopes of the first-level variables “MF” and “task” obtained a significant variance component between subjects ($p = .00$; $p = .02$, respectively). No significant cross-level interaction effects were found (all $p > .05$) (Fig. 3; Appendix A, Table A.2).

3.1.3. Physical task: Box placement accuracy

Neither MF nor the exoskeleton were significantly associated with box placement accuracy (M_1: $\widehat{\beta_{MF}} = -0.45, p = .84$; $\widehat{\beta_{Exo}} = -0.87, p = .69, \omega^2 < -.001$). Furthermore, no significant difference in the accuracy was found between task 1 and 2 (M_1: $\widehat{\beta_{Task2}} = -0.09, p = .97, \omega^2 < -.001$). When constructing the MLM, the ground platform was used as

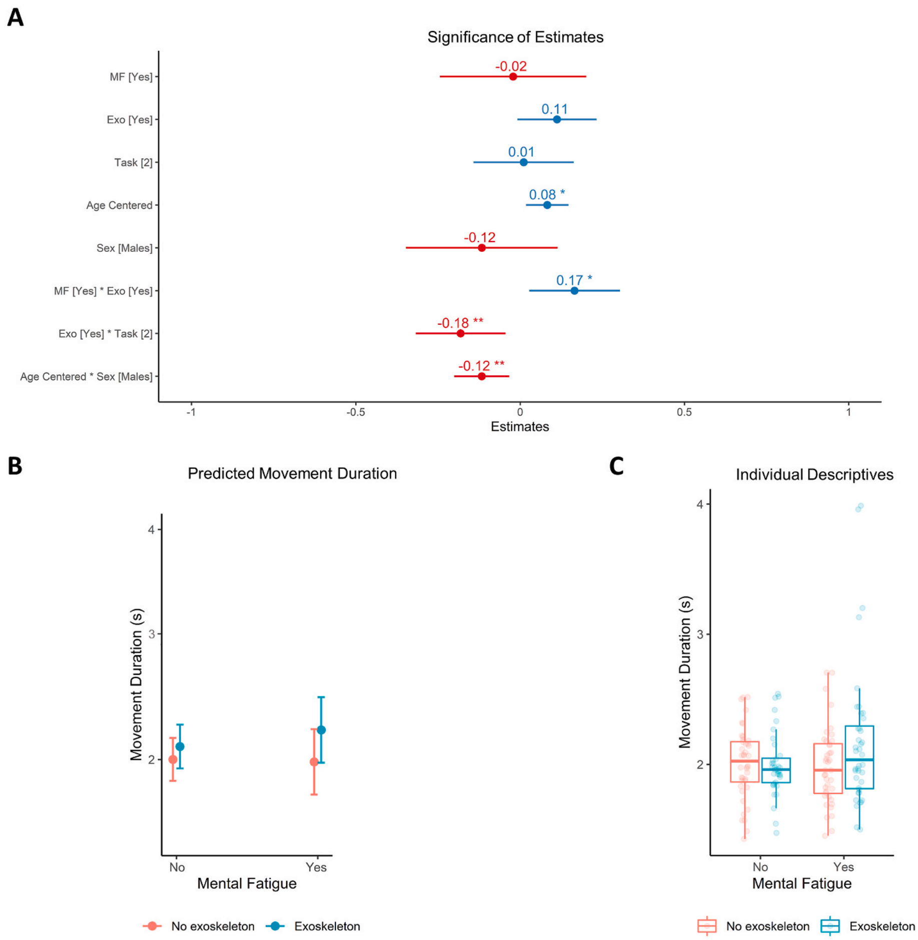

Fig. 3. (A) Statistical significance of each included parameter of the multilevel model constructed for movement duration. Significance codes: *** (p < .001); ** (p < .01); * (p < .05). (B) Mean predicted values of movement duration with 95% confidence intervals. Movement duration significantly increased when mentally fatigued and wearing the Laevo exoskeleton (p = .02) compared to the absence of both interventions. (C) Individual datapoints obtained during the experimental trials regarding movement duration.

reference category. Assuming all other variables constant, when transferring the box to the pelvic platform, a significantly higher accuracy was obtained ($p < .001$). Importantly, accuracy scores depend on sex and age, further details can be found in Appendix A, Table A.3).

3.1.4. M-VAS scores

Timepoint 1 (pre task 1) was used as reference category for the MLM (Appendix A, Table A.4). Contrasts of the three other timepoints were requested as additional comparison. No significant association was found between M-VAS scores and wearing an exoskeleton (all $p > .05$). No significant difference between the MF- and NoMF-group were found, except for timepoint 3 (pre task 2) and 4 (post task 2) as compared to timepoint 1, where the MF-group indicated higher scores than the NoMF-group ($\widehat{\beta_{time3:MF}} = 2.62, p = .002, \omega^2 = .16$) (Figs. 4 and 5). After completing the first dual task, M-VAS scores significantly increased ($\widehat{\beta_{time2}} = 0.92, p = .04, \omega^2 = .32$). Using "post task 1" as reference, M-VAS scores significantly increased after performing the Stroop task ($\widehat{\beta_{time3:MF}} = 3.02, p < .001, \omega^2 = .16$). The control task did not affect MVAS-scores ($\widehat{\beta_{time3:NoMF}} = 0.04, p = 1, \omega^2 = .16$). Furthermore, when using "pre task 2" as reference category, we learn that M-VAS scores significantly decrease after the performance of dual task in the MF-group ($\widehat{\beta_{time4:MF}} = 0.62, p = .05, \omega^2 = .16$). This was, however, not the case in the NoMF-group ($\widehat{\beta_{time4:NoMF}} = 0.25, p = .9, \omega^2 = .16$).

3.1.5. B-VAS

No significant association between B-VAS scores and wearing the exoskeleton was found (M$_1$: $\widehat{\beta_{Exo}} = -0.42, p = .64$). Furthermore, there was no significant discrepancy between B-VAS scores of dual tasks 1 and

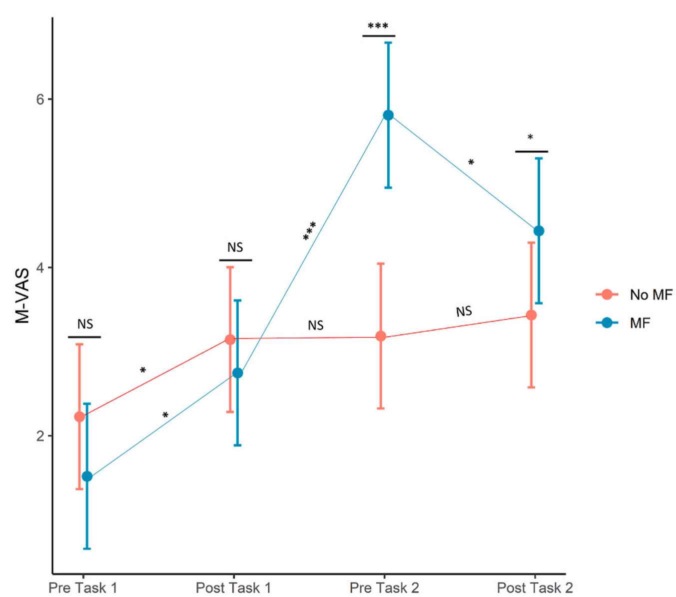

Fig. 4. Mean predicted M-VAS scores throughout the experiment with 95% confidence intervals. Significance codes: *** (p < .001); ** (p < .01); * (p < .05); NS (not significant). In the mental fatigue (MF) group, the Stroop task significantly increased M-VAS scores. No significant difference was found for the control group.

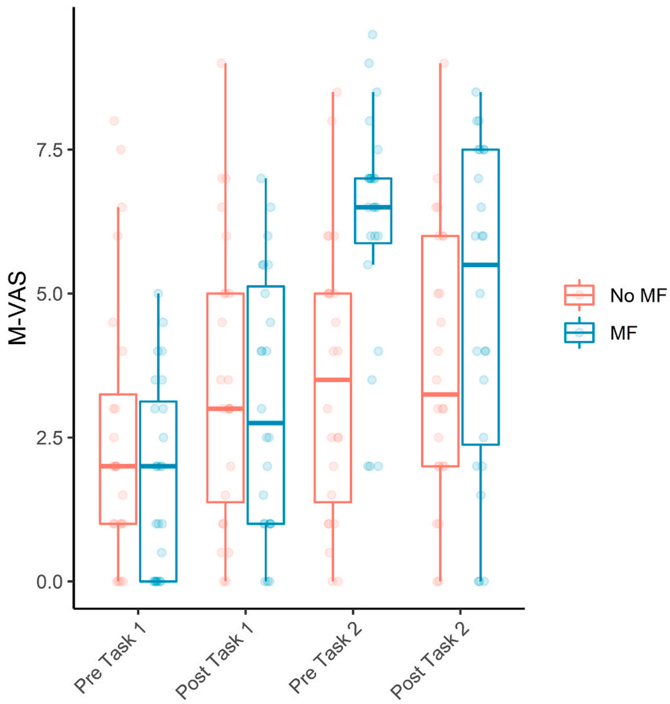

Fig. 5. Individual descriptives of M-VAS scores throughout the experiment. MF indicates the mental fatigue conditions, NoMF the control trials for mental fatigue.

2 (M4: $\widehat{\beta_{Time4}} = 0.04, p = .84, \omega^2 = -.01$). When watching the neutral documentary, boredom scores significantly decreased with an estimated 2.08 points compared to scores obtained after task 1 (M4 : $\widehat{\beta_{time3}} = -2.08, p = .01, \omega^2 = -.01$). However, for the stroop task, scores significantly increased with an estimated 2.32 points compared to the control task (M4 : $\widehat{\beta_{MF:time3}} = 4.40, p < .001, \omega^2 = .25$). The slope of the first-level variable "MF" obtained a significant variance component between subjects (p = .04). However, no significant cross-level interaction effects were found (all p > .05) (Appendix A, Table A.5).

3.1.6. NASA-TLX

MF, the exoskeleton and the task were not associated with changes in scores of mental demand, physical demand, effort or performance (all p > .05). However, frustration scores after the performance of task 2 significantly increased for males compared to task 1 (M_4: $\widehat{\beta_{task2}} = 17.50$, $p < .001, \omega^2 = .06$). Contrary to males, scores for females significantly decreased compared to dual task 1 (M_4: $\widehat{\beta_{task2:sex}} = -20.42, p = .01$, $\omega^2 = .03$). When wearing the exoskeleton scores significantly decreased for males in task 2 compared to the no-exoskeleton condition (M_4: $\widehat{\beta_{task2:exo}} = -18.75, p = .01, \omega^2 = .08$). Importantly, this effect is also sex-dependant (M_4: $\widehat{\beta_{exo:sex:task2}} = -20.42$, $p = .01$, $\omega^2 = .06$). Furthermore, assuming all other variables constant, temporal demand scores significantly increased with an estimated 8.75 points when wearing the exoskeleton, (M_3: $\widehat{\beta_{Exo}} = 8.75, p = .03, \omega^2 < .001$). However, when mentally fatigued and wearing the exoskeleton, the exoskeleton contributed to a significant decrease of an estimated 5.84 points compared to not wearing the exoskeleton (M_3: $\widehat{\beta_{MF:Exo}} = -11.88$, $p = .04, \omega^2 = .04$) (Appendix A, Table A.6-A.11).

3.2. Control variables

The functionality of the exoskeleton regarding the different work performance parameters was not associated with sex or age (all p > .05). However, main effects of age and sex were found to be associated with different work performance parameters (p < 0.01). Appendix A can be consulted for further details since this was beyond the scope of this research. Interestingly, females obtained significantly higher M-VAS scores than males ($\widehat{\beta_{sex}} = 1.40, p = .03, \omega^2 = .39$). Furthermore, a significant interaction effect between age and sex was found (Fig. 6): older females are estimated to obtain lower M-VAS scores compared to the younger female population ($\widehat{\beta_{age:sex}} = -1.01, p < .001, \omega^2 = .70$) while older males are estimated to report higher M-VAS scores ($\widehat{\beta_{age}} = 0.50, p < .001, \omega^2 = .60$) (Fig. 6; Appendix A, Table A.5-A.11).

4. Discussion

To the best of our knowledge, this study was the first to investigate the combined effect of wearing an exoskeleton and being mentally fatigued on simulated industrial dual task (cognitive and physical task) performance. In summary, the combined effects of MF and wearing an exoskeleton hampered work performance in terms of increased movement duration. Main effects of MF and the exoskeletons were not present. Secondary outcomes (age and sex) did not influence the functionality of the exoskeleton regarding work performance but did influence the degree of MF.

4.1. Effect of mental fatigue on dual task performance

4.1.1. Manipulation check of mental fatigue

Participants were more mentally fatigued in the MF condition according to the M-VAS scores. However, inter-individual differences were observed (Fig. 5), indicating a variable effectiveness of the Stroop task (Holgado et al., 2020). Despite the Stroop task being customized to maintain arousal to effectively induce MF, some participants were nevertheless bored or frustrated, indicating that the task may need more alterations. These findings further confirm that MF remains inherently correlated to different psychological constructs, such as motivation, boredom and arousal, which further contribute to the interindividual differences in MF-effects (Habay et al., 2021).

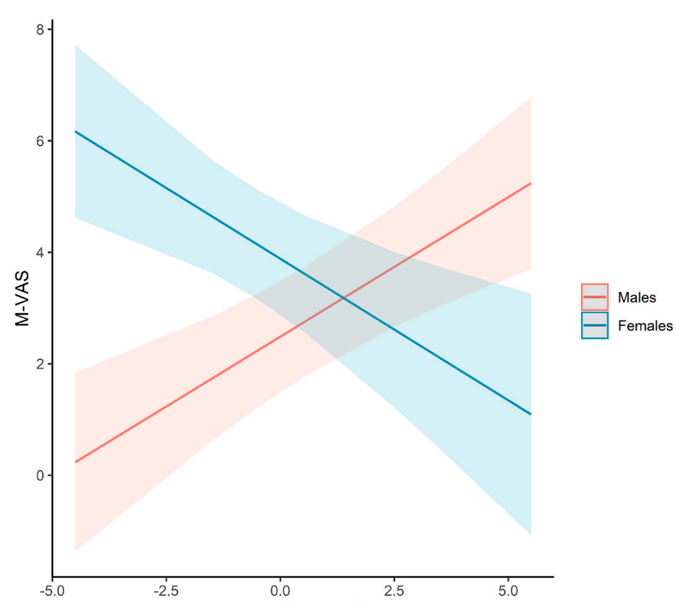

Fig. 6. Predicted M-VAS scores according to age and sex. A significant interaction effect between the two variables is found for all tasks: older females report decreased M-VAS scores compared to younger females, males report with increasing age higher M-VAS scores.

4.1.2. Dual task performance

No main effects of MF were found on dual task performance. Literature showed that, by increasing requirements of cognitive resources during task performance, effects of MF are likely to be present (Martin et al., 2018). During manufacturing work, increased cognitive demands can be expected when a cognitive task is incorporated in a physical task e.g., following a step-by-step manufacturing process that is cued by digital instructions. In this experiment we simulated this by means of a dual task. However, due to the relatively extensive familiarisation period and a minimal level of dual task complexity (cyclic performance without any incongruencies), it is likely that in order to perform this dual task, participants required only a limited amount of cognitive functions since a certain level of automatization would be set in (Mawase et al., 2018), hence, minimising MF-effects (Pendleton et al., 2016). Furthermore, when using the Stroop task, we primarily affect the executive function network (more specifically, response inhibition and attention), located in the prefrontal cortex (Angius et al., 2019). However, due to the extensive familiarisation period and the cyclic requirements of the task (being the lift/lower movements performed every 6 s plus the congruent calculation task), we assume that the dual task was performed in a more automated manner, minimising the requirement of cognitive resources. Therefore, the use of one's previously targeted executive functions would be limited during the dual task performance, minimising the, the effects of the Stroop task on work performance (Giboin and Wolff, 2019). This mechanism is also observed in task switching studies, where successive tasks are developed with the goal to address different brain regions from those required in the previous task (Eich et al., 2016; Wang et al., 2020; Ward et al., 2019). This to minimise the accumulation of mental fatigue in specific brain regions (Lorist et al., 2000).

We assume that the current experimental design of the dual task and the extensive familiarisation period attenuated a main effect of MF. However, these results support the implementation of job rotations, defined as alternating workers between tasks that require different skills and responsibilities (Huang, 1999). Job rotations are already implemented in many manufacturing companies but mainly focus on limiting the exposure to physical risk factors of musculoskeletal disorders (Rodriguez and Barrero, 2017). The same principle of rotations can incorporate employees' cognitive functions, where different cognitive functions are addressed by each task to enhance the recovery of the possibly depleted functions which could safeguard employees from developing mental fatigue. Although no significant main effects of MF on work performance were found during the specific developed task in this research, it is important to note that in other settings or during other tasks, this could be the case. Therefore, to optimize employees' health and the production process, industrial companies should consider the mental as well as the physical requirements per task to accurately assess the need for job rotations.

4.2. Effect of the Laevo exoskeleton on dual task performance

The exoskeleton was associated, with a decrease in movement duration during task 2 (= −0.18, $p < .01$, $\omega^2 = .04$). Since this was not found during task 1, we hypothesise that, despite an intensive familiarisation period, a learning effect was still present. Researchers should therefore be aware of this result when evaluating exoskeletons and possibly include more familiarisation periods to objectify a plateau in the learning curve. No other significant associations were found between the exoskeleton and work performance parameters. This was however challenging to predict due to the previously mentioned task-dependency of the device (Baltrusch et al., 2018; Bosch et al., 2016; Luger et al., 2021). Furthermore, the exoskeleton did not affect the subjective MF feeling (Fig. 3). However, similar to work performance, this lack of significant association between the Laevo exoskeleton and M-VAS scores could also strongly depend on the task performed with the exoskeleton. Therefore, prior to the implementation of an exoskeleton on the work floor, a thorough evaluation in similar working conditions should be considered to correctly balance potential benefits and shortcomings of the exoskeleton.

4.3 Effect of the interaction of mental fatigue and the Laevo exoskeleton on dual task performance.

Importantly, the interaction of both interventions contributed to a significant increase in movement duration. This is also corroborated by the significant decrease in the temporal demand domain of the NASA-TLX, which indicated that participants were less hasty to complete the dual task in the MF-Exo condition compared to baseline condition. We assume that, although no significant difference in NASA-TLX mental demand scores was found, combining MF with the exoskeleton, increased cognitive pressure and therefore added to task complexity. This likely facilitated the trade-off between movement duration and box placement accuracy, which during the other experimental conditions, was not present to a degree of significance, due to the, as hypothesised before, relatively low task complexity. In the MF-Exo group, to maintain the proposed task goal despite increased complexity, participants compromised movement duration. This phenomenon is also known as the speed-accuracy trade-off (Rozand et al., 2015), which means that when participants need to reach a target as quickly and accurately as possible, they must compromise on either speed or accuracy. This is in line with our results, since we did not find a significant change in box placement accuracy.

This suggests that working with the Laevo exoskeleton when mentally fatigued, will negatively affect the production process and possibly the industrial company. Increasing production cycle times or loss in quality hinders the efficiency of the production process, costing the company a competitive advantage towards other manufacturing companies (Taifa and Vhora, 2019). Furthermore, workers could get frustrated or demotivated, since they are no longer able to perform at their former level. These negative impressions relate to deviant actions such as counter-productive work behaviour, or turnover intention (Colbert et al., 2004). This result might also contribute to a more negative user experience of the exoskeleton which could hinder successful implementation of other devices in the future (Elprama et al., 2022).

Future research is needed to validate these results since this significant increase is generated by a limited amount of datapoints that scored well-above average (Fig. 3, plot C). When excluding these datapoints, the ratio of the number of observations to the number of parameter estimates would be too limited. By doing so, significance regarding movement duration disappeared (although pointing towards the same direction, i.e. an increase in movement duration when combining MF and the exoskeleton). After reassuring no errors during the data gathering or data-entry process were made, we decided to therefore include these results.

Furthermore, determining which other biopsychosocial factors, besides MF, may interact with the functionality of an exoskeleton is also recommended in this manner. Other exoskeletons should be subjected to a similar evaluation to investigate a possible analogue impact of MF. We suggest that industrial companies make a thorough assessment of the robotic device, e.g. cost-benefit analysis, complemented by a meticulous testing period, before implementing exoskeletons in the work floor. Furthermore, it seems also important to accurately inform workers about the capabilities as well as any limitations of the device so that expectations are aligned, and user-acceptance is enhanced (Elprama et al., 2022).

4.3. Limitations and future research

Some limitations regarding the present study should be addressed. The simplification of a laboratory study with one type of exoskeleton could challenge the translation of these results to the field (De Bock et al., 2021). Furthermore, a relatively small sample size was included. Therefore, in-field testing with different types of exoskeletons and a larger sample size should validate these results. In addition, this research focussed on one task within the functionality of the exoskeleton at hand. Other manufacturing tasks should be investigated for the effects of MF and the exoskeleton to solidify these findings. Furthermore, to better understand the impact of MF on work performance, the complexity of the dual task could be augmented to require similar activation of cognitive functions as during the performance of the Stroop task, e.g., include response inhibition, attention and/or task switching. Moreover, the significant decrease in movement duration during dual task 2 when wearing the exoskeleton indicated that participants were, although familiarised extensively, not sufficiently adjusted to the device when they performed dual task 1. Future research should therefore investigate the learning curve of working with an exoskeleton since no literature is yet available regarding adaptation periods. Additionally, no differences were found between males and females regarding the effect of the exoskeleton. However, we did not address other known challenges e.g., discomfort, which could influence user-experience and potentially be amplified when mentally fatigued. Lastly, we want to point out that MF was only subjectively evaluated through a visual analogue scale. Although challenging, more objective measurements for MF like an electroencephalogram could be considered.

5. Conclusion

The present study investigated the influence of MF and the Laevo exoskeleton on work performance i.e., cognitive task performance measured through a calculation task and physical task performance measured through movement duration and accuracy of placement, during a simulated manufacturing task. MF nor the exoskeleton contributed to a change in work performance. However, when mentally fatigued and wearing the exoskeleton, work performance worsened; more specifically, movement duration increased. These findings are the first to suggest an important interaction between functionality of the exoskeleton and one's psychobiological state, more specifically, mental fatigue. Industrial workers and management should be aware of these possible contra productive effects and manage expectations when implementing robotic devices on the work floor. Moreover, when designing and evaluating exoskeletons, researchers should be aware of MF, and possible other biopsychosocial factors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix A. Multilevel regression models

Table A.1
MLM results for the stepwise model building procedure of calculation task accuracy predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Calculation task						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	98.73 (0.18)***	98.73 (0.18)***	98.73 (0.12)***	98.73 (0.12)***	Id. M_3	
MF_{yes}		NS				
Exo_{yes}		NS				
$Task_2$		NS				
$MF_{yes}*Exo_{yes}$		NS				
$MF_{yes}*Task_2$		NS				
$Exo_{yes}*Task_2$		NS				
$MF_{yes}*Exo_{yes}*Task_2$		NS				
Age			0.18 (0.05)**	0.18 (0.05)**		0.75
$Sex_{females}$			NS			
$Task_2*Age$			NS			
$Task_2*Sex_{females}$			NS			
$Sex_{females}*Age$			NS			
$Task_2*Sex_{females}*Age$			NS			
Random part						
σ_e^2	0.30 (0.55)	0.30 (0.55)	0.07 (0.26)	0.07 (0.26)		
σ_{u0}^2	0.73 (0.85)	0.73 (0.85)	0.73 (0.85)	0.73 (0.85)		
σ_{u1}^2				NS		
σ_{u2}^2				NS		
σ_{u3}^2				NS		
Model quality						
Deviance	258.46	258.46	246.71	246.71		
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	11.75 (Df = 1)***	0.00 (Df = 0)		
AIC	266.10	266.10	261.76	261.76		
BIC	273.80	273.80	272.02	272.02		
Pseudo-R^2 (fixed effects)	0.00	0.00	0.22	0.22		
Pseudo-R^2 (total)	0.29	0.29	0.29	0.29		

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.0.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Time.

Table A.2
MLM results for the stepwise model building procedure of movement duration predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Movement duration						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	2.04 (0.08)***	2.00 (0.09)***	1.97 (0.11)	2.00 (0.10)	2.00 (0.10)	
MF_{yes}		- 0.02 (0.06)	- 0.02 (0.06)	- 0.02 (0.11)	- 0.02 (0.11)	−0.07
Exo_{yes}		0.09 (0.08)	0.09 (0.08)	0.11 (0.06)**	0.11 (0.06)	0.06
$Task_2$		0.01 (0.06)	0.01 (0.06)	0.01 (0.08)	0.01 (0.08)	0.03
$\underline{MF_{yes}*Exo_{yes}}$		0.20 (0.09)*	0.20 (0.09)*	0.17 (0.07)*	0.17 (0.07)*	0.03
$\underline{Exo_{yes}*Task_2}$		- 0.19 (0.09)*	- 0.19 (0.09)*	- 0.18 (0.07)**	- 0.18 (0.07)**	0.04
$MF_{yes}*Task_2$		NS				
$MF_{yes}*Exo_{yes}*Task_2$		NS				
Age			−0.04 (0.03)	- 0.03 (0.03)	- 0.03 (0.03)	0.03
$Sex_{females}$			0.17 (0.14)	0.12 (0.12)	0.12 (0.12)	−0.0002
$\underline{Sex_{females}*Age}$			0.12 (0.05)*	0.12 (0.04)**	0.12 (0.04)**	0.45
$Task_2*Age$			NS			
$Task_2*Sex_{females}$			NS			
$Task_2*Sex_{females}*Age$			NS			
$Sex_{females}*Age*MF_{yes}$					NS	
$Sex_{females}*Age*Task_2$					NS	
Random part						
σ^2_e	0.05 (0.23)	0.05 (0.23)	0.04 (0.20)	0.04 (0.19)	0.04 (0.19)	
σ^2_{u0}	0.09 (0.30)	0.08 (0.28)	0.08 (0.28)	0.05 (0.19)	0.05 (0.19)	
σ^2_{u1}				0.10 (0.32)	0.10 (0.32)	
σ^2_{u2}				NS	NS	
σ^2_{u3}				0.03 (0.22)	0.03 (0.22)	
Model quality						
Deviance	86.23	67.40	60.21	3.05	3.05	
χ^2	0.00 (Df = 0)	18.84 (Df = 5)**	7.18 (Df = 3)	57.16 (Df = 5)***	57.16 (Df = 5)	
AIC	95.56	105.76	117.75	72.28	72.28	
BIC	104.71	130.16	151.30	121.07	121.07	
Pseudo-R^2 (fixed effects)	0.00	0.07	0.24	0.22	0.22	
Pseudo-R^2 (total)	0.38	0.45	0.49	0.70	0.70	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
The variable age was centered.
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 156 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Task.

Table A.3
MLM results for the stepwise model building procedure of box placement accuracy predicted by mental fatigue, exoskeleton, task, platform, control variables and their interactions.

Box placement accuracy						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	94.11 (0.82)***	94.11 (0.82)***	85.43 (0.56)***	85.43 (0.56)***	Id. M_3	
MF_{yes}		NS				
Exo_{yes}		NS				
$Task_2$		NS				
$MF_{yes}*Exo_{yes}$		NS				
$Exo_{yes}*Task_2$		NS				
$MF_{yes}*Task_2$		NS				

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Table A.3 (*continued*)

Box placement accuracy						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
$MF_{yes}*Exo_{yes}*Task_2$		NS				
$Platform_{pelvic}$			14.61 (0.48)***	14.61 (0.48)***		0.87
$Sex_{females}$			7.84 (0.86)***	7.84 (0.86)***		0.78
Age			0.34 (0.18)	0.34 (0.18)		0.58
$Platform_{pelvic}*Sex_{females}$			−7.69 (0.74)***	−7.69 (0.74)***		0.44
$Platform_{pelvic}*Age$			−0.66 (0.13)***	−0.66 (0.13)***		0.16
$Age*Sex_{females}$			0.87 (0.27)*	0.87 (0.27)*		0.57
$Platform_{pelvic}*Age*Task_2$			NS			
$Platform_{pelvic}*Age*Task_2$			NS			
$Platform_{pelvic}*Age*Task_2$			NS			
Random part						
σ_e^2	3.41 (1.85)	3.41 (1.85)	0.91 (0.95)	0.91 (0.95)		
$\sigma_{\mu0}^2$	41.35 (6.43)	41.35 (6.43)	4.43 (2.10)	4.43 (2.10)		
σ_{u1}^2				NS		
σ_{u2}^2				NS		
σ_{u3}^2				NS		
Model comparison						
Deviance	951.14	951.14	627.65	627.65		
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	323.49 (Df = 6)***	0.00 (Df = 0)		
AIC	955.77	955.77	645.65	645.65		
BIC	964.68	964.68	677.07	677.07		
Pseudo-R^2 (fixed effects)	0.00	0.00	0.88	0.88		
Pseudo-R^2 (total)	0.08	0.08	0.90	0.90		

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males; Platform = Ground.
N = 144 observations.
The variable age was centered. s.e. = standard error; Df = degrees of freedom;
σ_e^2 = variance of individual-level residual errors; σ_{u0}^2 = variance of group-level residual errors; σ_{u1}^2 = variance component of for the regression coefficient of MF; σ_{u2}^2 = variance component of for the regression coefficient of Exo; σ_{u3}^2 = variance component of for the regression coefficient of Time.

Table A.4
MLM results for the stepwise model building procedure of M-VAS scores predicted by mental fatigue, exoskeleton, time, control variables and their interactions.

M-VAS						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	3.65 (0.48) ***	2.56 (0.58)***	1.53 (0.48)**	1.53 (0.51)	1.53 (0.51)	
$Time_2$		NS		0.92 (0.45)*	0.92 (0.45)*	0.32
$Time_3$		NS		0.96 (0.45)*	0.96 (0.45)*	
$Time_4$		1.21 (0.49)*	1.21 (0.49)*	1.21 (0.45)**	1.21 (0.45)**	
MF_{yes}		−0.71 (0.49)	−0.71 (0.49)	−0.71 (0.60)	−0.71 (0.60)	0.07
Exo_{yes}		NS				
$MF_{yes}*Exo_{yes}$		NS				
$MF_{yes}*Time_2$		NS	NS	NS	NS	
$MF_{yes}*Time_3$		3.33 (0.69)***	3.33 (0.69)***	3.33 (0.63)***	3.33 (0.63)***	0.16
$MF_{yes}*Time_4$		NS	1.71 (0.69)*	1.71 (0.63)*	1.71 (0.63)*	
$Exo_{yes}*Time_2$		NS	NS	NS	NS	
$Exo_{yes}*Time_3$		NS	NS	NS	NS	
$Exo_{yes}*Time_4$		NS	NS	NS	NS	
$MF_{yes}*Exo*Time_2$		NS	NS	NS	NS	
$MF_{yes}*Exo*Time_3$		NS	NS	NS	NS	
$MF_{yes}*Exo*Time_4$		NS	NS	NS	NS	
Age			0.50 (0.13)***	0.50 (0.13)***	0.50 (0.13)***	0.60
$Sex_{females}$			1.40 (0.51)*	1.40 (0.51)*	1.40 (0.51)*	0.39
$Age*Sex_{females}$			−1.01 (0.20)***	−1.01 (0.20)***	−1.01 (0.20)***	0.70
$Age*Sex_{females}*Time_2$			NS			
$Age*Sex_{females}*Time_3$			NS			
$Age*Sex_{females}*Time_4$			NS			
$MF_{yes}*Age*Sex_{females}$					NS	
Random effects						
σ_e^2	2.54 (1.59)	2.63 (1.62)	0.56 (0.75)	1.05 (1.03)	1.05 (1.03)	

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Table A.4 (*continued*)

M-VAS	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
$\sigma^2_{\mu 0}$	4.40 (2.10)	2.88 (1.70)	2.88 (1.70)	2.40 (1.56)	2.40 (1.56)	
σ^2_{u1}				1.87 (1.37)	1.87 (1.37)	
σ^2_{u2}				NS		
σ^2_{u3}				NS		
Model comparison						
Deviance	856.38	772.76	752.87	737.30	737.30	
χ^2	0.00 (Df = 0)	83.62 (Df = 7)***	19.89 (Df = 3)***	15.57 (Df = 2)***	15.57 (Df = 2)	
AIC	862.04	792.46	784.43	772.73	772.73	
BIC	871.81	825.03	826.78	821.59	821.59	
Pseudo-R^2 (fixed effects)	0.00	0.22	0.51	0.51	0.51	
Pseudo-R^2 (total)	0.37	0.59	0.59	0.66	0.66	

Significance codes: *** (p < .001); ** (p < .01); * (p < .05).
Reference categories: Time = Pre task 1 (1); MF = No; Exo = No; Sex = Males.
N = 192 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Time.

Table A.5
MLM results for the stepwise model building procedure of B-VAS scores predicted by mental fatigue, exoskeleton, time, control variables and their interactions.

B-VAS	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	4.51 (0.61)***	4.67 (0.73)***	4.67 (0.73)***	4.67 (0.71)***	4.67 (0.71)***	
MF_{yes}		−0.31 (0.62)	−0.31 (0.62)	−0.31 (0.73)	−0.31 (0.73)	0.17
Exo_{yes}		NS				
<u>$Time_3$</u>		−2.08 (0.62)***	−2.08 (0.62)***	−2.08 (0.58)**	−2.08 (0.58)**	−0.01
$Time_4$		0.04 (0.62)	0.04 (0.62)	0.04 (0.58)	0.04 (0.58)	
<u>MF_{yes}*$Time_3$</u>		4.40 (0.88)***	4.40 (0.88)***	4.40 (0.82)***	4.40 (0.82)***	0.25
MF_{yes}*$Time_4$		NS	NS	NS	NS	
MF_{yes}*Exo_{yes}		NS				
Exo_{yes}*$Time_3$		NS				
Exo_{yes}*$Time_4$		NS				
MF_{yes}*Exo_{yes}*$Time_3$		NS				
MF_{yes}*Exo_{yes}*$Time_4$		NS				
Age			NS			
$Sex_{females}$			NS			
Age (centered) *$Sex_{females}$			NS			
$Time_3$*Age			NS			
$Time_4$*Age			NS			
$Time_3$*$Sex_{females}$			NS			
$Time_4$*$Sex_{females}$			NS			
$Time_3$*Age*$Sex_{females}$			NS			
$Time_4$*Age*$Sex_{females}$			NS			
MF*$Sex_{females}$*$Time_4$					NS	
MF_{yes}*Age*$Time_4$					NS	
MF_{yes}*$Sex_{females}$*Age					NS	
Random part						
σ^2_e	3.945 (1.986)	4.061 (2.015)	4.061 (2.015)	4.022 (2.005)	4.022 (2.005)	
$\sigma^2_{\mu 0}$	6.056 (2.461)	4.663 (2.159)	4.663 (2.159)	4.058 (2.014)	4.058 (2.014)	
σ^2_{u1}				2.330 (1.526)	2.330 (1.526)	
σ^2_{u2}				NS		
σ^2_{u3}				NS		
Model quality						
Deviance	693.08	653.4	653.48	646.79	646.79	
χ^2	0.00 (Df = 0)	39.60 (Df = 5)***	0.00 (Df = 0)	6.69*	0.00 (Df = 0)	
AIC	698.28	665.99	665.99	663.03	663.03	

(*continued on next page*)

Table A.5 (*continued*)

B-VAS	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
BIC	707.19	689.74	689.74	692.73	692.73	
Pseudo-R^2 (fixed effects)	0.00	0.14	0.14	0.14	0.14	
Pseudo-R^2 (total)	0.39	0.54	0.54	0.60	0.60	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Time = post task 1 (2); MF = No; Exo = No; Sex = Males.
N = 144 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ_e^2 = variance of individual-level residual errors; σ_{u0}^2 = variance of group-level residual errors; σ_{u1}^2 = variance component of for the regression coefficient of MF; σ_{u2}^2 = variance component of for the regression coefficient of Exo; σ_{u3}^2 = variance component of for the regression coefficient of Time.

Table A.6
MLM results for the stepwise model building procedure of Nasa-TLX (mental demand) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Nasa-TLX Mental Demand	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*
Intercept	51.33 (6.99)***	51.33 (6.99)***	51.33 (6.99)***	51.33 (6.99)***	Id. M_3
MF_{yes}		NS			
Exo_{yes}		NS			
$Task_2$		NS			
MF_{yes}*Exo_{yes}		NS			
MF_{yes}* $Task_2$		NS			
Exo_{yes}* $Task_2$		NS			
MF_{yes}*Exo_{yes}* $Task_2$		NS			
Age			NS		
$Sex_{females}$			NS		
Age*$Sex_{females}$			NS		
$Task_2$*Age			NS		
$Task_2$*$Sex_{females}$			NS		
$Task_2$*Age*$Sex_{females}$			NS		
			NS		
Random part					
σ_e^2	561.5 (23.70)	561.5 (23.70)	561.5 (23.70)	561.5 (23.70)	
σ_{u0}^2	203.8 (14.28)	203.8 (14.28)	203.8 (14.28)	203.8 (14.28)	
σ_{u1}^2				NS	
σ_{u2}^2				NS	
σ_{u3}^2				NS	
Model quality					
Deviance	819.48	819.48	819.48	819.48	
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	
AIC	819.80	819.80	819.80	819.80	
BIC	827.49	827.49	827.49	827.49	
Pseudo-R^2 (fixed effects)	0.00	0.00	0.00	0.00	
Pseudo-R^2 (total)	0.73	0.73	0.73	0.73	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ_e^2 = variance of individual-level residual errors; σ_{u0}^2 = variance of group-level residual errors; σ_{u1}^2 = variance component of for the regression coefficient of MF; σ_{u2}^2 = variance component of for the regression coefficient of Exo; σ_{u3}^2 = variance component of for the regression coefficient of Time.

Table A.7
MLM results for the stepwise model building procedure of Nasa-TLX (physical demand) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Nasa-TLX Physical Demand					
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4:Model with cross-level interactions
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*
Intercept	38.29 (6.03)***	38.29 (6.03)***	38.29 (6.03)***	39.11 (5.98)***	39.11 (5.98)***
MF_{yes}		NS			
Exo_{yes}		NS			
$Task_2$		NS			
MF_{yes}*Exo_{yes}		NS			
MF_{yes}*$Task_2$		NS			
Exo_{yes}*$Task_2$		NS			
MF_{yes}*Exo_{yes}*$Task_2$		NS			
Age			NS		
$Sex_{females}$			NS		
Age*$Sex_{females}$			NS		
$Task_2$*Age			NS		
$Task_2$*$Sex_{females}$			NS		
$Task_2$*Age*$Sex_{females}$			NS		
MF_{yes}*$Sex_{females}$*$Task_2$					NS
MF_{yes}*Ag*$Task_2$					NS
MF_{yes}*$Sex_{females}$*Age					NS
Random part					
σ^2_e	412.6 (20.31)	412.6 (20.31)	412.6 (20.31)	226 (15.05)	226 (15.05)
$\sigma^2_{\mu0}$	186.7 (13.66)	186.7 (13.66)	186.7 (13.66)	122 (11.05)	122 (11.05)
σ^2_{u1}				226.4 (15.05)	226.4 (15.05)
σ^2_{u2}				NS	
σ^2_{u3}				NS	
Model quality					
Deviance	808.56	808.56	808.56	791.23	791.23
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	17.33 (Df = 2)***	17.33 (Df = 2)
AIC	809.17	809.17	809.17	795.86	795.86
BIC	816.87	816.87	816.87	808.68	808.68
Pseudo-R^2 (fixed effects)	0.00	0.00	0.00		
Pseudo-R^2 (total)	0.69	0.69	0.69		

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
s.e. = standard error; Df = degrees of freedom;
σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Time.

Table A.8
MLM results for the stepwise model building procedure of Nasa-TLX (effort) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Nasa-TLX Effort					
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*
Intercept	45.16 (5.91)***	45.16 (5.91)***	45.16 (5.91)***	45.16 (5.91)***	Id. M_3
MF_{yes}		NS			
Exo_{yes}		NS			
$Task_2$		NS			
MF_{yes}*Exo_{yes}		NS			
MF_{yes}*$Task_2$		NS			
Exo_{yes}*$Task_2$		NS			
MF_{yes}*Exo_{yes}*$Task_2$		NS			
Age			NS		
$Sex_{females}$			NS		
Age*$Sex_{females}$			NS		
$Task_2$*Age			NS		
$Task_2$*$Sex_{females}$			NS		
$Task_2$*Age*$Sex_{females}$			NS		
Random part					

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Table A.8 (*continued*)

Nasa-TLX Effort					
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions
σ_e^2	396.3 (19.91)	396.3 (19.91)	396.3 (19.91)	396.3 (19.91)	
σ_{u0}^2	180 (13.42)	180 (13.42)	180 (13.42)	180 (13.42)	
σ_{u1}^2				NS	
σ_{u2}^2				NS	
σ_{u3}^2				NS	
Model quality					
Deviance	805.01	805.01	805.01	805.01	
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	
AIC	805.67	805.67	805.67	805.67	
BIC	813.36	813.36	813.36	813.36	
Pseudo-R^2 (fixed effects)	0.00	0.00	0.00	0.00	
Pseudo-R^2 (total)	0.69	0.69	0.69	0.69	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ_e^2 = variance of individual-level residual errors; σ_{u0}^2 = variance of group-level residual errors; σ_{u1}^2 = variance component of for the regression coefficient of MF; σ_{u2}^2 = variance component of for the regression coefficient of Exo; σ_{u3}^2 = variance component of for the regression coefficient of Time.

Table A.9
MLM results for the stepwise model building procedure of Nasa-TLX (frustration) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Nasa-TLX Frustration						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	42.24 (6.25)***	42.24 (6.25)***	42.24 (6.25)***	39.17 (5.59)***	26.83 (8.82)*	
MF_{yes}		NS				
Exo_{yes}		NS			11.07 (8.16)	−0.09
$Task_2$		NS			17.50 (5.25)***	0.06
MF_{yes}*Exo_{yes}		NS				
MF_{yes}*$Task_2$		NS				
Exo_{yes}*$Task_2$		NS			−18.75 (7.25)*	0.08
MF_{yes}*Exo_{yes}*$Task_2$		NS				
Age			NS			
$Sex_{females}$			NS		25.24 (11.43)	0.12
Age*Sex			NS			
$Task_2$*Age			NS			
$Task_2$*$Sex_{females}$			NS		−20.42 (7.42)**	0.03
$Task_2$*Age*Sex			NS			
MF_{yes}*$Sex_{females}$*$Task_2$					NS	
MF_{yes}*Age*$Task_2$					NS	
MF_{yes}*$Sex_{females}$*Age					NS	
Exo_{yes}*$Sex_{females}$					−4.00 (11.54)	−0.04
Exo_{yes}*$Sex_{females}$*$Task_2$					22.92 (10.25)*	0.06
Exo_{yes}*Age*$Task_2$					NS	
Exo_{yes}*$Sex_{females}$*Age					NS	
Random part						
σ_e^2	425.7 (20.63)	425.7 (20.63)	425.7 (20.63)	319.5 (17.87)	333.5 (18.26)	
σ_{u0}^2	344.0 (18.55)	344.0 (18.55)	344.0 (18.55)	185.9 (13.63)	157.6 (12.56)	
σ_{u1}^2				300.4 (17.33)	313.2 (17.70)	
σ_{u2}^2				253.0 (15.91)	271.2 (16.47)	
σ_{u3}^2				NS	NS	
Model quality						
Deviance	860.76	860.76	860.76	838.03	821.30	
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	22.73 (Df = 5)***	16.735 (Df = 9)*	
AIC	861.30	861.30	861.30	848.80	779.47	
BIC	869.00	869.00	869.00	869.31	838.45	

(*continued on next page*)

Table A.9 (*continued*)

Nasa-TLX Frustration						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Pseudo-R^2 (fixed effects)	0.00	0.00	0.00		0.17	
Pseudo-R^2 (total)	0.55	0.55	0.55		0.82	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Time.

Table A.10
MLM results for the stepwise model building procedure of Nasa-TLX (performance) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

Nasa-TLX Performance					
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*
Intercept	38.02 (4.43)***	38.02 (4.43)***	38.02 (4.43)***	38.02 (4.43)***	Id. M_3
MF_{yes}		NS			
Exo_{yes}		NS			
$Task_2$		NS			
MF_{yes}*Exo_{yes}		NS			
MF_{yes}*$Task_2$		NS			
Exo_{yes}*$Task_2$		NS			
MF_{yes}*Exo_{yes}*$Task_2$		NS			
Age			NS		
$Sex_{females}$			NS		
Ag*$Sex_{females}$			NS		
$Task_2$*Age			NS		
$Task_2$*$Sex_{females}$			NS		
$Task_2$*Age*$Sex_{females}$			NS		
Random part					
σ^2_e	206.8 (14.38)	396.3 (19.91)	396.3 (19.91)	396.3 (19.91)	
σ^2_{u0}	228.2 (15.11)	180 (13.42)	180 (13.42)	180 (13.42)	
σ^2_{u1}				NS	
σ^2_{u2}				NS	
σ^2_{u3}				NS	
Model quality					
Deviance	818.01	818.01	818.01	818.01	
χ^2	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	0.00 (Df = 0)	
AIC	819.24	819.24	819.24	819.24	
BIC	826.94	826.94	826.94	826.94	
Pseudo-R^2 (fixed effects)	0.00	0.00	0.00	0.00	
Pseudo-R^2 (total)	0.48	0.48	0.48	0.48	

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ^2_e = variance of individual-level residual errors; σ^2_{u0} = variance of group-level residual errors; σ^2_{u1} = variance component of for the regression coefficient of MF; σ^2_{u2} = variance component of for the regression coefficient of Exo; σ^2_{u3} = variance component of for the regression coefficient of Time.

Table A.11
MLM results for the stepwise model building procedure of Nasa-TLX (temporal demand) scores predicted by mental fatigue, exoskeleton, task, control variables and their interactions.

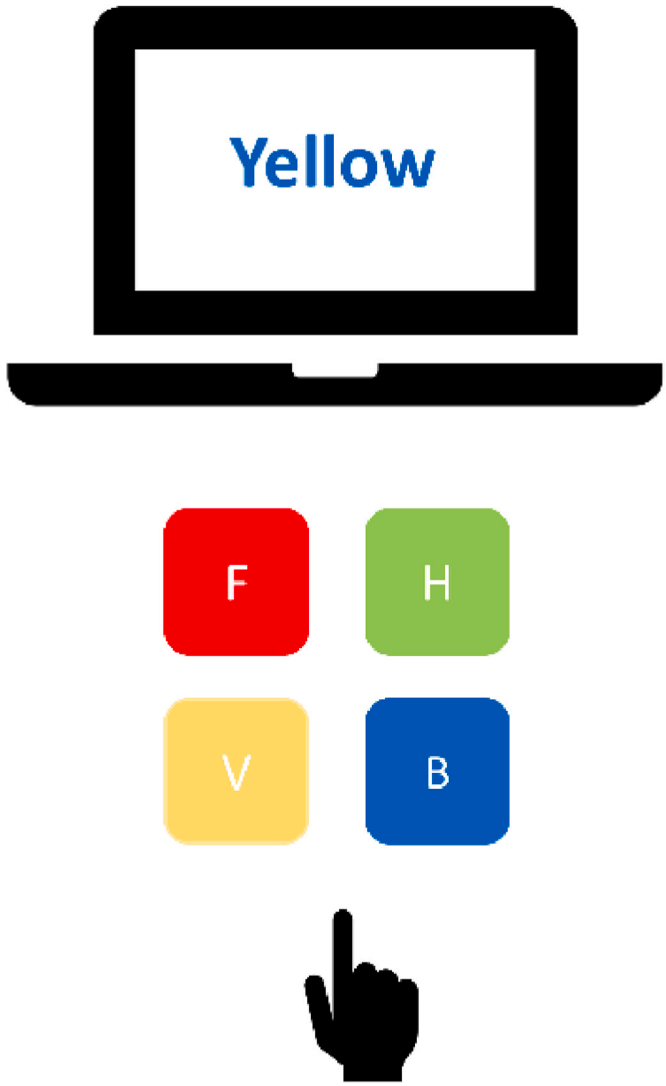
Nasa-TLX Temporal demand						
	M_0: Intercept-only model	M_1: Model with first-level predictors	M_2: Model with second-level predictors	M_3: Model with random slopes	M_4: Model with cross-level interactions	Omega squared final model (ω^2)
Fixed part	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	*Coef. (s.e.)*	
Intercept	41.09 (5.93)***	36.67 (6.40)***	36.67 (6.40)***	36.67 (6.40)***	Id. M_3	
MF_{yes}		6.04 (3.93)	6.04 (3.93)	6.04 (3.93)		−0.01
Exo_{yes}		8.75 (3.93)	8.75 (3.93)	8.75 (3.93)*		<0.001
MF_{yes}*Exo_{yes}		−11.88 (5.56)*	−11.88 (5.56)*	−11.88 (5.56)*		0.04
$Task_2$		NS				
MF_{yes}*$Task_2$		NS				
Exo_{yes}*$Task_2$		NS				
MF_{yes}*Exo_{yes}*$Task_2$		NS				
Age			NS			
$Sex_{females}$			NS			
Age*$Sex_{females}$			NS			
$Task_2$*Age			NS			
$Task_2$*$Sex_{females}$			NS			
$Task_2$*Age*$Sex_{females}$			NS			
Random part						
σ_e^2	398.6 (19.96)	399.3 (19.98)	399.3 (19.98)	399.3 (19.98)		
σ_{u0}^2	191.4 (13.83)	185.7 (13.63)	185.7 (13.63)	185.7 (13.63)		
σ_{u1}^2				NS		
σ_{u2}^2				NS		
σ_{u3}^2				NS		
Model quality						
Deviance	810.27	804.67	804.67	804.67		
χ^2	0.00 (Df = 0)	5.59 (Df = 3)	5.59 (Df = 3)	5.59 (Df = 3)		
AIC	810.91	798.34	798.34	798.34		
BIC	818.61	813.72	813.72	813.72		
Pseudo-R^2 (fixed effects)	0.00	0.02	0.02	0.02		
Pseudo-R^2 (total)	0.68	0.69	0.69	0.69		

Significance codes: *** ($p < .001$); ** ($p < .01$); * ($p < .05$).
Reference categories: Task = 1; MF = No; Exo = No; Sex = Males.
N = 96 observations.
The variable age was centered.
s.e. = standard error; Df = degrees of freedom; σ_e^2 = variance of individual-level residual errors; σ_{u0}^2 = variance of group-level residual errors; σ_{u1}^2 = variance component of for the regression coefficient of MF; σ_{u2}^2 = variance component of for the regression coefficient of Exo; σ_{u3}^2 = variance component of for the regression coefficient of Time.

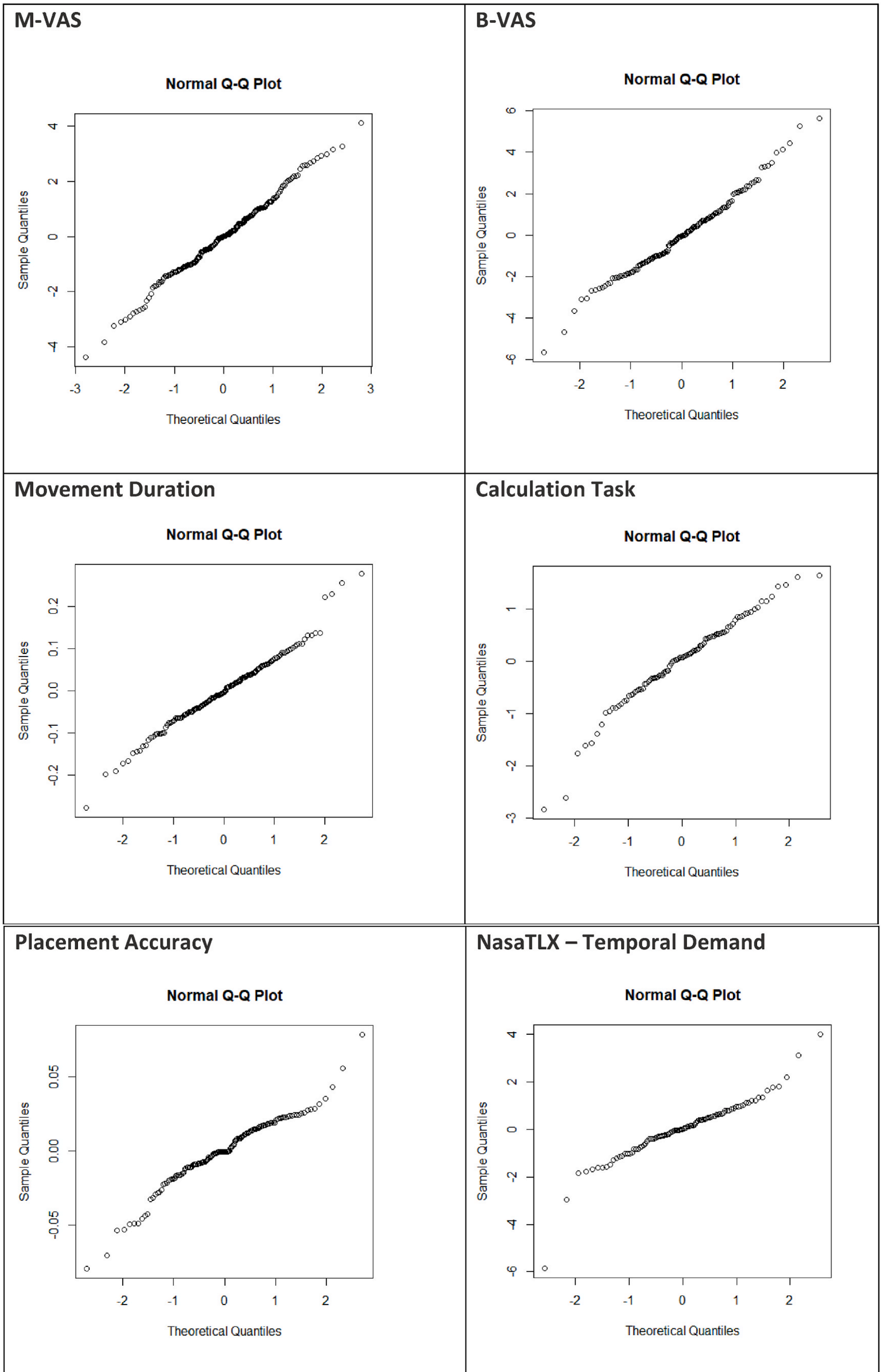
Appendix B. Coding of the included variables

Variable	Coding
MF	0 = No MF
	1 = MF
Exo	0 = No Exo
	1 = Exo
Time	1 = Pre task 1
	2 = Post task 1
	3 = Pre task 2
	4 = Pre task 2
Task	1 = Task 1
	2 = Task 2
Platform	0 = Ground platform
	1 = Pelvic platform
Type	0 = Lifting
	1 = Lowering
Sex	0 = Male
	1 = Female

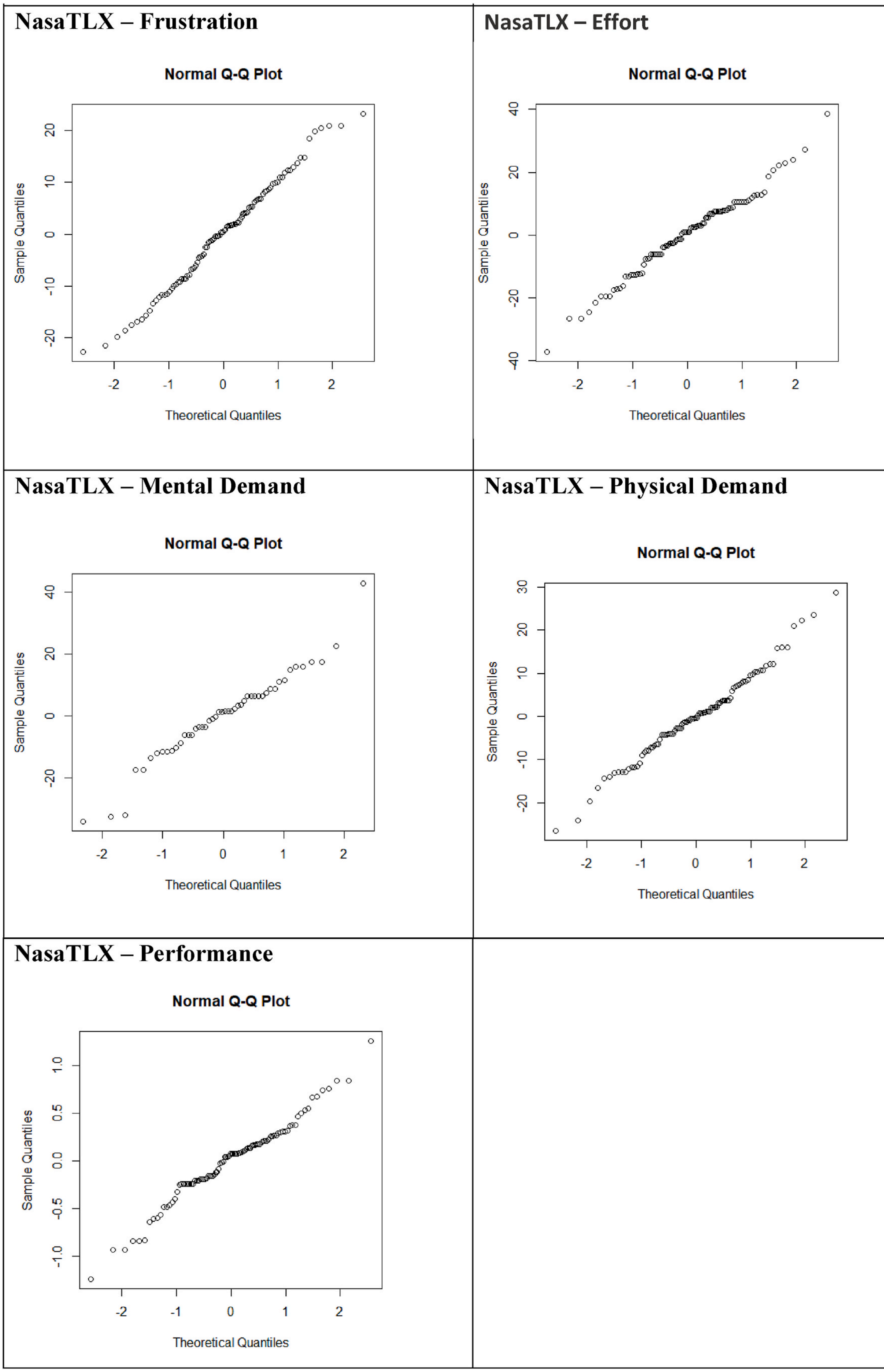
Dummy coding was used for the represented parameters. If not mentioned otherwise in the multilevel regression models, zero indicates the reference level for the parameter estimates.



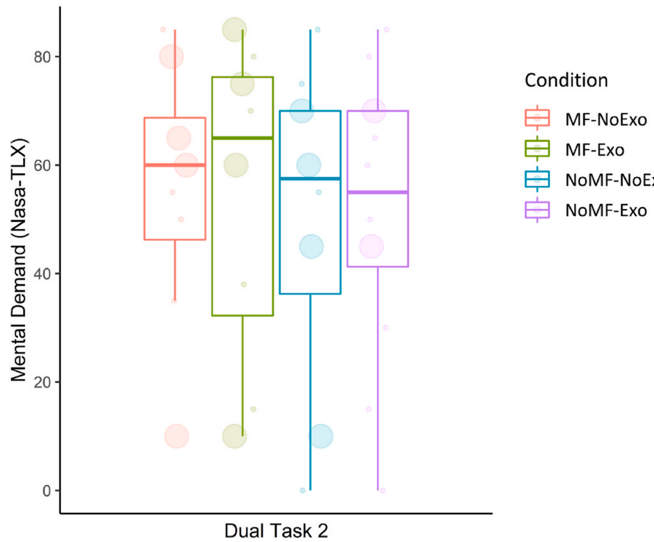
Appendix C. Schematic overview of the Stroop task.



Appendix D. Inspection of the normality of the residuals of the final multilevel regression models.



Appendix D. (*continued*).



Appendix E. Mental demand scores (Nasa-TLX) obtained after the performance of dual task 2 in each experimental group. MF = Mental Fatigue; NoMF = No Mental Fatigue; Exo = Exoskeleton, NoExo = No Exoskeleton.

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