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Article

Changes in Human Motor Behavior during the Familiarization with a Soft Back-Support Occupational Exoskeleton

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Abstract: Soft back exoskeletons are aimed at reducing musculoskeletal effort during manual handling tasks, contributing to the prevention of low back disorders like lumbar strains and sprains or intervertebral disk problems. However, large differences in their biomechanical effects are observed in the literature. A possible explanation could be the lack or disparity of familiarization protocols with the exoskeleton. The aim of this experimental study was to characterize the familiarization process with a soft back-support occupational exoskeleton and determine the time needed to stabilize biomechanical variables. Participants carried out 6 familiarization sessions of 1 h to the CORFOR[®] soft back-exoskeleton. Joint kinematics, postural stability, exoskeleton pressure perception, muscle activity, and performance were measured at the beginning of the first session and at the end of each session during stoop and squat liftings. Results showed that back kinematics, performance, and exoskeleton pressure perception changed during the first sessions and stabilized after sessions 3 or 4, depending on the variable. The authors recommend a familiarization protocol for the CORFOR[®] soft back-exoskeleton of 4 sessions of 1 h duration. This recommendation could help CORFOR[®] users, for instance, in the automotive industry, the food retail industry, or the agriculture field.

Keywords: motor control; motion analysis; motor learning; exoskeleton; biomechanics



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1. Introduction

About 40% of workers in Europe suffered from musculoskeletal disorders (MSDs), frequently located in the back region [1,2]. Exoskeletons can be passive, using springs or elastics, or active, using one or more actuators [3]. Exoskeletons have also been categorized by the body part they are designed to support, such as the back, upper-limb, lower-limb, or full-body [4,5]. Active or passive occupational back exoskeleton devices aim to prevent back MSDs from providing assistance to the spine during tasks involving forward bending [3,6].

Theurel and Desbrosses (2019) [6] reviewed and confirmed the effectiveness of passive back exoskeletons to reduce lumbar muscular demand but also reported inconsistent results. For instance, from 10% to around 50% reductions in back muscle activity have been reported in manual handling tasks [7] and during static postures [8,9]. These large differences might be attributed to different factors, such as the design of the exoskeleton or the level of assistance [6]. Additional harmful effects have been observed with the use of exoskeletons: discomfort, heat, reduced range of motion [10], or larger postural oscillations [11]. Koopman et al. (2019) [12] also reported alterations in movement execution, with reduced lifting speed while using a back robotic exoskeleton during manual lifting tasks. Furthermore, exoskeletons have several limitations: they are task-specific, can interfere with the working environment, decrease productivity, or even induce discomfort.

These aforementioned modifications of the motor behavior could be the result of the exoskeleton use [6], but also of the familiarization process with the device [13,14]. Indeed, any motor behavior is subject to evolution during the adaptation to the new parameters of

a task, during which motor learning is needed to reach the same motor behavior as prior to the new parameter's exposure [15]. Accordingly, measuring the motor behavior during the early stage of exoskeleton use might lead to non-representative motor behavior during long-term exoskeleton use. Put differently, if familiarization with the exoskeleton is not achieved, the assessment of its potential benefits can be misestimated. This might also be the source of the divergent results within the literature because of varying familiarization periods.

Some authors worked on the familiarization process with walking exoskeletons [13,14,16]. For instance, Diamond-Ouellette et al. (2022) [16] recently observed that a 9-day familiarization period with the use of a multi-joint exoskeleton by soldiers led to a diminution of the metabolic cost during walking. However, these authors did not characterize the evolution of this variable during the familiarization protocol. Contrariwise, Galle et al. (2013) [14] showed a decrease in metabolic cost during the first 18.5 min of walking with an ankle exoskeleton, followed by a stabilization. Moreover, Panizzolo et al. (2019) [13] studied a longer familiarization process based on five sessions lasting 20 min. These authors showed a diminution of the metabolic cost when walking with a hip exoskeleton until the third session, followed by a stabilization. Despite the discrepancy in exoskeleton types, this familiarization model assessed on walking exoskeletons may be transferred to passive occupational back exoskeletons.

However, among the 51 papers cited in three literature reviews about exoskeletons [3,6,17], 25 articles did not mention any familiarization process before measurements. In the remaining 26 studies, only nine described the task and duration used for the familiarization. Among these studies, different familiarization durations were used, ranging from 10 min [18] to 4 sessions of 97 min duration [11], but none of them actually verified the stabilization of the motor behavior, possibly leading to non-representative data about the effects of the exoskeleton use. In addition, changes and steady states of biomechanical metrics during familiarization are currently unknown. But these parameters, such as trunk or back muscle activity, back, hip, and knee kinematics [9,19], movement's execution [20], or postural stability [11], would certainly be relevant to point out the influence of an exoskeleton's use and be representative of the familiarization process. It is therefore of interest to investigate the effects of exoskeleton use on motor behavior, possibly related to MSDs, to verify that participants have reached a steady state prior to the evaluation, meaning that their motor behavior does not change anymore with practice. This rationale mostly arises from an experimental issue, as most of the studies cited in these literature reviews were short-term lab-based studies (except Smets' study in 2019 [10], which was a long-term worksite study). By doing so, recommendations about a familiarization protocol/duration could be made to ensure (i) a relevant evaluation of the benefits of the exoskeleton and (ii) that workers would operate with stable motor behavior.

The aim of this study was to characterize the familiarization process with a soft back-support occupational exoskeleton and determine the time needed to stabilize studied variables such as back muscle activity, back, hip, and knee kinematics, movement's execution, postural stability, workload perception, and performance as evidence of motor behavior. We hypothesized that, along with the familiarization time, an evolution (increase or decrease depending on the variable) would be followed by a stabilization for each variable.

2. Materials and Methods

2.1. Population

Eighteen male participants (21.5 ± 2.3 years, 178.3 ± 3 cm, 69.6 ± 6.2 kg) inexperienced with any exoskeleton use were included in the present protocol. As sex might be a confounding factor [21], only male participants were included in this study. The following non-inclusion criteria were applied in accordance with the ethical committee: vulnerable people, neurological disorders, back orthopedic disorders (scoliosis), use of drugs (antidepressant, antiepileptic), injury or pain in the back or upper and lower limbs

during the last 3 months. This study was conducted according to the guidelines of the Declaration of Helsinki.

2.2. Task Habituation

First, participants were familiarized with three experimental tasks to minimize the effect of habituation on the tasks during the exoskeleton familiarization protocol. Participants were asked to lift an 8 kg box from the ground to a visual target while using two different techniques, i.e., stoop and squat. The upper target was 105 cm above the ground and 30 cm ahead of the tip of their feet. When the box was on the ground, the handles were at a height of 15 cm. A cadence of 15 liftings per minute was prescribed and controlled by a metronome. Twelve lifts were repeated for each condition. The 8 kg mass agreed with the French normalization association recommendations AFNOR X35-109 [22]. The stoop technique (STOOP) consisted of lifting the box while minimizing knee flexion. Therefore, participants had to bend their trunks to lower their hands at the appropriate height to grasp the box at ground level. The squat technique (SQUAT) consisted of lifting the box with knee flexion while maintaining the back as straight as possible. STOOP and SQUAT were chosen because these tasks are frequently used in the field and compared in the literature [21,23,24]. In addition, these typical manual handling tasks, a third task, called the precision task (PRECI), consisted of moving a handle with a ring tip along a rod with an oscillating trajectory (Figure 1). Participants were asked to perform the task in an upright position, from the starting point to midway and back to the starting point, the fastest possible without touching the rod with the ring, representing an error. They were free to choose their bending position and to move their feet if needed. The only constraint was to always take the handle with their preferred hand. Priority was given to the absence of errors instead of speed. Participants were asked to perform PRECI three times at each repetition. The rationale for including PRECI was to involve the participant in a global task with a great range of motion of the trunk and with accuracy and speed challenges. All tasks were demonstrated to participants, and the task order was randomized to control any bias (order effect, fatigue). Overall, this habituation period was composed of 3 sessions of 20 min with an intersession rest of 48 h to 72 h.

2.3. Familiarization Protocol

The familiarization protocol (Figure 2) was composed of six sessions of 1 h duration over two weeks, with an intersession rest of 48 h to 72 h, according to the principles of motor learning [25,26]. It consisted of a set of different general tasks (walking, lifting, manual handling, and fine handling) performed several times in order to improve, as much as possible, the motor learning related to the use of the exoskeleton [27].

While wearing the exoskeleton, participants had to perform the PRECI task (1) and then grasped a box of 8 kg on the ground, walked 4 m with this box (2), and put it down with the stoop technique (3). After that, they had to lift the box on stool 1 in front of them using the stoop technique (3). At this point, they turned around the stool 1 for a quarter turn, grasped the box, and brought it back to the ground with a stoop technique (4). Then, they lifted the box from chair 1 on their left. While facing chair 1, they moved the box to chair 2 (5). Then, they lowered the box in front of stool 2 using the squat technique (6), prior to a whole lifting cycle around stool 2 with the squat technique (7). Afterwards, they walked over two meters (8) until they grasped a pen on the floor (9) and reached the precision task bench (10). Finally, participants performed the precision task again (11), prior to executing the whole sequence of tasks in reverse order. This set of tasks was performed in two minutes. Two minutes of rest were also given between each set. In this way, 15 sets were carried out during a 1 h session of the familiarization protocol with the exoskeleton.

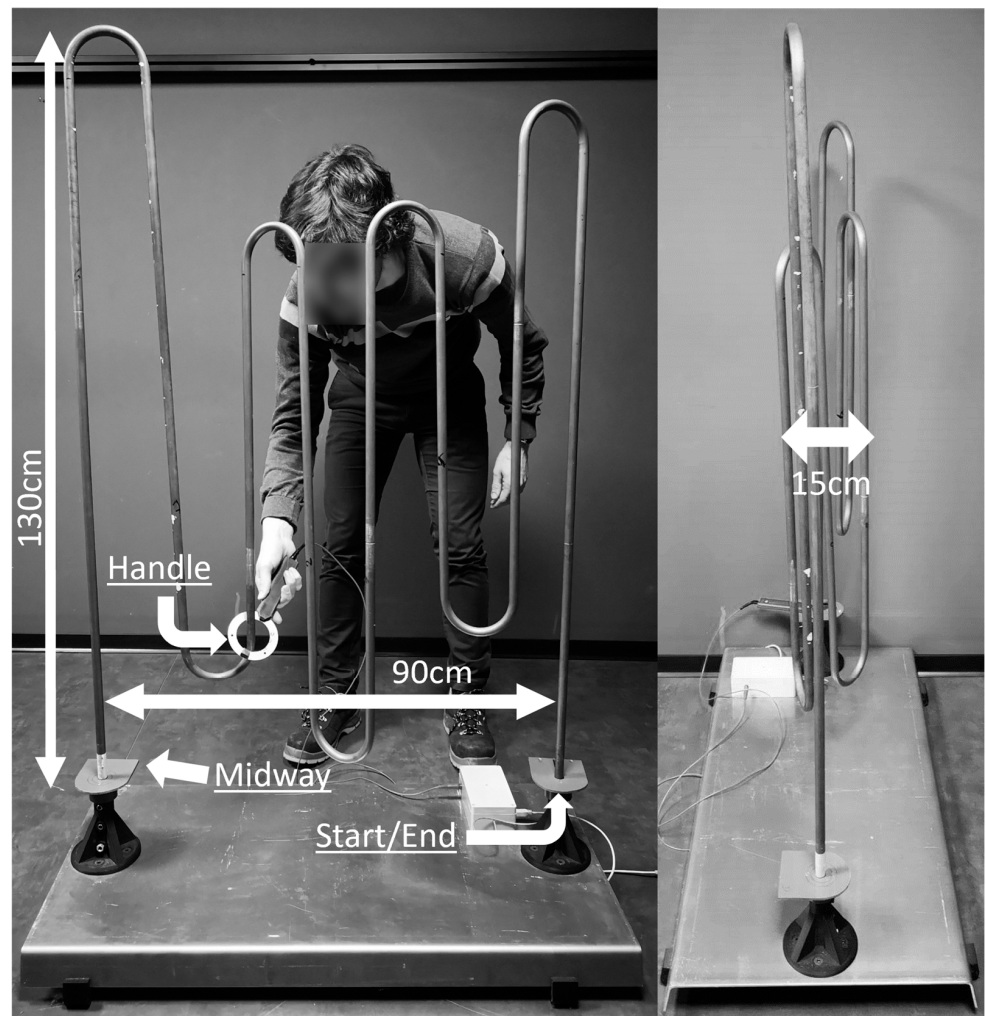


Figure 1. Frontal and side views of the device used for the precision task (PREC). An Arduino board connected the copper tube to the steel ring attached to the plastic handle.

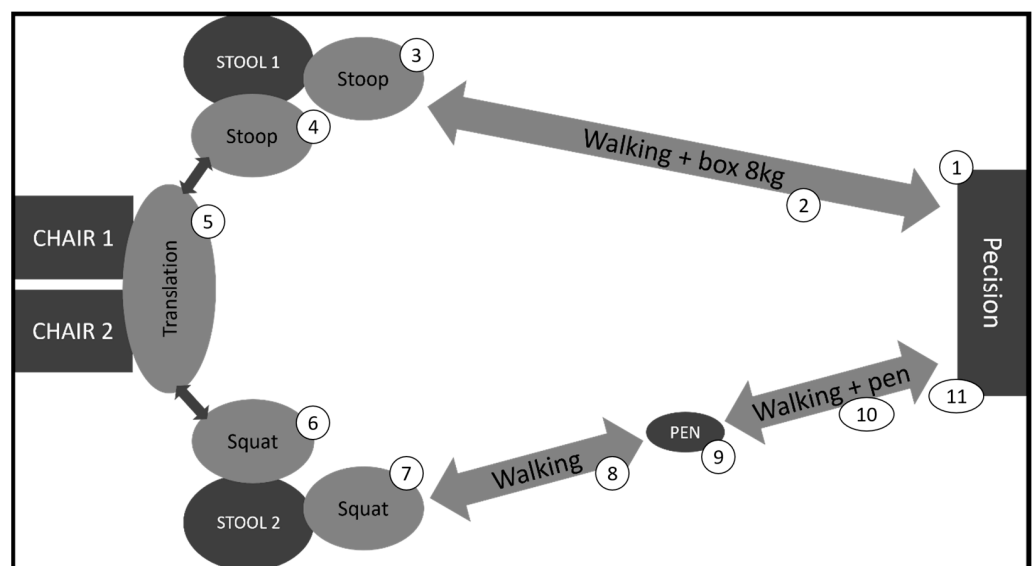


Figure 2. Familiarization protocol.

2.4. Evaluation

Participants were evaluated while performing the three experimental tasks (STOOP, SQUAT, and PRECI) for each familiarization session. The execution of the tasks was visually controlled by the investigators. During the first session and before the start of the familiarization protocol, a first measurement was conducted without the exoskeleton as a control condition (PRE-CON), followed by a second one with the exoskeleton (PRE-1). After the familiarization protocol, measurements were taken with the exoskeleton (POST-1). During sessions 2 to 6, participants completed the familiarization protocol prior to the measurement (POST-2 to POST-6).

2.5. Materials

Participants wore a CORFOR[®] exoskeleton (Figure 3), which is a soft back-support exoskeleton (CORFOR[®]-V2, Villemus, France). It is composed of two elastic bands attached to the shoulders and to the knees thanks to pairs of straps. Hip and back flexion stretch the elastic bands, which assist passively in the extension of the hip and the back during manual material handling. Soft back exoskeletons have been described to reduce lumbar neuromuscular demand from 6% [21] to 14% [28,29] depending on the model. In addition, its known effects during manual material handling [21], the CORFOR[®] presents the additional advantages of providing an exoskeleton solution for an affordable price and with ease of use, yielding a large use in different companies.



Figure 3. A participant wearing the exoskeleton with the measurement's setup.

Biomechanical recordings were completed during the SQUAT and STOOP tasks. Eight Qualisys cameras (MIQUS M5, Qualisys, Göteborg, Sweden; 2D resolution = 4 MP; 3D resolution = 0.07 mm) were placed around participants to track 25 reflective markers taped to the skin (Figure 3). Marker trajectories were recorded at 150 Hz. The markerset [30,31]

was composed of 16 markers placed on anatomical landmarks (left and right antero-superior iliac spines, left and right postero-superior iliac spines, right greater trochanter, right medial and lateral femoral epicondyles, right medial and lateral malleolus, sacral to cervical vertebrae at S1, L4, L2, T12, T2, C7 levels, right radius styloid process) and 8 tracking markers (2 iliac crests, 3-markers cluster for the thigh, 3-markers cluster for the shank). Three other markers were taped on the corners of the box handled by the subjects. Participants stood on a triaxial force plate (Bertec Corp., Columbus, OH, USA; error due to linearity or hysteresis = 0.2%; Resolution of output signal = 0.02%) used to sample center of pressure (CoP) positions at a sampling rate of 1000 Hz. Surface electromyography (EMG, sampling rate of 2000 Hz) was used to record Gluteus Maximus (GM), Tensor Fascia Latae (TFL), Obliquus Externus (OE), Rectus Abdominis (RA), and Erector Spinae (ES) muscle activity on the right side (Trigno™, Delsys, Natick, MA, USA; Figure 3). EMG signals were synchronized with all other data. The electrode placement and the skin preparation were conducted in accordance with SENIAM recommendations [32].

Also, the Nasa Task Load Index (NASA-TLX) [33] was used to assess the global perceived workload. Participants had to answer the questionnaire at the end of each condition. Questions treated six factors: mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants were asked to attribute a weight to each factor. The global score was the sum of the weighted scores of each factor. Moreover, Likert scales were proposed to the participants to evaluate their back muscles exertion and the perceived pressures due to the exoskeleton on the trapezius, armpits, buttocks, and knees. These scales ranged from 0 (nothing) to 10 (very, very hard).

2.6. Analysis

Marker trajectories were filtered using a Butterworth 4th-order 5 Hz lowpass filter. The three markers taped to the box enabled us to compute the position of the box center. Lower and higher peak values of box center vertical positions were used to split the lifting task into upward and downward phases. By means of a cubic interpolation, each phase was time-normalized into 100 data points. Right hip and right knee joint angles were calculated in three dimensions using a custom MATLAB program following the recommendations of Cappozzo et al. (1995) [34] and Wu et al. (2002) [31]. Maximum knee flexion and hip flexion angles were computed for each cycle. Back curvature was assessed in the sagittal plane using S1, L4, L2, T12, T2, and C7 markers. Three segments (C7-T2, T12-L2, L4-S1) were used to calculate lumbar flexion (T12-L2-L4-S1) and thoracic flexion (C7-T2-T12-L2), as previously carried out with inertial measurement units [9]. Maximum lumbar and thoracic flexion angles were computed for each cycle. As movement smoothness can be representative of the subject's expertise [35], the smoothness of the right wrist was evaluated using the resultant speed of the marker placed on the right radius styloid process during the upward phase. The resultant speed of the marker was used as the input for the spectral arc length function proposed by Balasubramanian et al. (2015) [20]. It evaluates the spectral arc-length metric that uses a movement speed profile's Fourier magnitude spectrum to quantify movement smoothness. The output smoothness value was negative, and smoother motion was represented by a value closer to zero.

Center of pressure data were filtered using a Butterworth 4th order lowpass filter at 10 Hz. The CoP trajectory was perturbed when the box touched the ground between each cycle. Therefore, data on CoP displacement were analyzed only when the box was off the ground (during both upward and downward phases). Confidence ellipse area (95%) and anteroposterior postural oscillation amplitude (difference between the maximum value and the minimum value of CoP position on the anteroposterior axis) were calculated to evaluate postural stability, as it can be influenced by the use of an exoskeleton [11].

EMG data were filtered using a bandpass 30–450 Hz Butterworth 4th order filter. The root mean squared (RMS) values were then calculated for each muscle and for each cycle. The mean value of the 10 cycles was computed for each muscle and for each condition and expressed relative to the muscle activity recorded during a reference task. This reference

task consisted of a forward jump as far as possible [36] and was performed prior to the familiarization protocol at the beginning of each session. The jump performance during the first session was marked in order to be reached again during subsequent sessions. Average RMS values over two broad jump attempts were used to normalize each muscle activity.

For hip and knee angles, back curvature, smoothness, confidence ellipse, postural oscillation amplitude, and EMG RMS, the mean value over 10 cycles was calculated.

An overall motor control performance was assessed during PRECI, as was the time needed to execute the task, and each error accounted for an additional 2 s lapse. The mean performance value was calculated over three attempts. The timed performance and the number of errors were assessed using an Arduino[®] Uno board and a custom Arduino[®] program.

2.7. Statistics

Results are presented as means \pm standard deviations (SD). Data normality were controlled using a Shapiro–Wilk test. If samples were normally distributed, a one-way repeated measures ANOVA (PRE-1, POST-1 to POST-6) was used to assess the effect of the familiarization protocol with the exoskeleton. Significant effects were further analyzed with post-hoc Tukey HSD pairwise comparisons in order to discern the evolution and stabilization phases. The evolution phase was characterized by statistical differences between sessions across time. The stabilization phase was characterized by a plateau with no statistical difference between the sessions that are part of the plateau. Familiarization was defined as any change from PRE-1, followed by a steady state. In addition, Student's paired *t*-tests were used to assess the effects of wearing the exoskeleton with respect to the control condition (PRE-CON). In the case of a stabilization phase, a *t*-test was performed to assess the effect of the exoskeleton between PRE-CON and PRE1, and another one between PRE-CON and the first session of the stabilization phase. If samples were not normally distributed, a Friedman's ANOVA (PRE-1, POST-1 to POST-6) was used instead of the parametric ANOVA. Significant effects were further analyzed with post-hoc Durbin-Conover pairwise comparisons. Wilcoxon tests were used instead of the Student's *t*-tests. A 5% significance level ($p < 0.05$) was set. A Bonferroni correction was adopted for *t*-tests ($p < 0.025$). Holm's correction was applied for Durbin-Conover pairwise comparisons. These analyses were performed using Jamovi 2.2.5 software (The Jamovi Project, 2022).

3. Results

Back curvature values were only altered over the familiarization protocol at the thoracic level (Figure 4). Indeed, the statistical analysis showed a significant main effect of familiarization on thoracic flexion for both STOOP ($p = 0.012$, $\eta^2 = 0.02$) and SQUAT ($p = 0.015$, $\eta^2 = 0.02$). For STOOP, post-hoc comparisons revealed that thoracic flexion in PRE-1 was significantly lower than POST-3, POST-4, and POST-6 ($p < 0.05$). Moreover, the Student's *t*-tests revealed that PRE-CON ($31.2 \pm 10.1^\circ$) was not different from PRE-1 ($28.7 \pm 10.8^\circ$; $p = 0.1$) but significantly lower than POST-3 ($33.2 \pm 9.4^\circ$; $p < 0.01$). For SQUAT, post-hoc comparisons revealed that only thoracic flexion in PRE-1 was significantly lower than in POST-3 and POST-6 ($p < 0.05$). Student's *t*-tests showed that PRE-CON ($27.6 \pm 10.2^\circ$) was not different from PRE-1 ($27.6 \pm 10.4^\circ$; $p = 0.9$) but was significantly lower than POST-3 ($31.7 \pm 10.3^\circ$; $p < 0.01$).

There was no statistical main effect of familiarization on lumbar flexion, hip flexion, knee flexion, or smoothness (Table 1).

Postural oscillations were also partially altered over the familiarization protocol (Table 2). There was a statistical main effect of familiarization on the confidence ellipse area for STOOP ($p = 0.002$, $W = 0.17$). Pairwise comparisons did not reveal a clear stabilization phase, as POST-6 yielded a smaller confidence ellipse value than POST-1 and POST-2 ($p \leq 0.001$) but not than PRE-1. There was also a statistical main effect on the confidence ellipse for SQUAT ($p = 0.02$, $W = 0.12$), but post-hoc tests could not tease out significant differences between sessions. The anteroposterior amplitude of CoP displacement was not significantly influenced by the familiarization protocol.

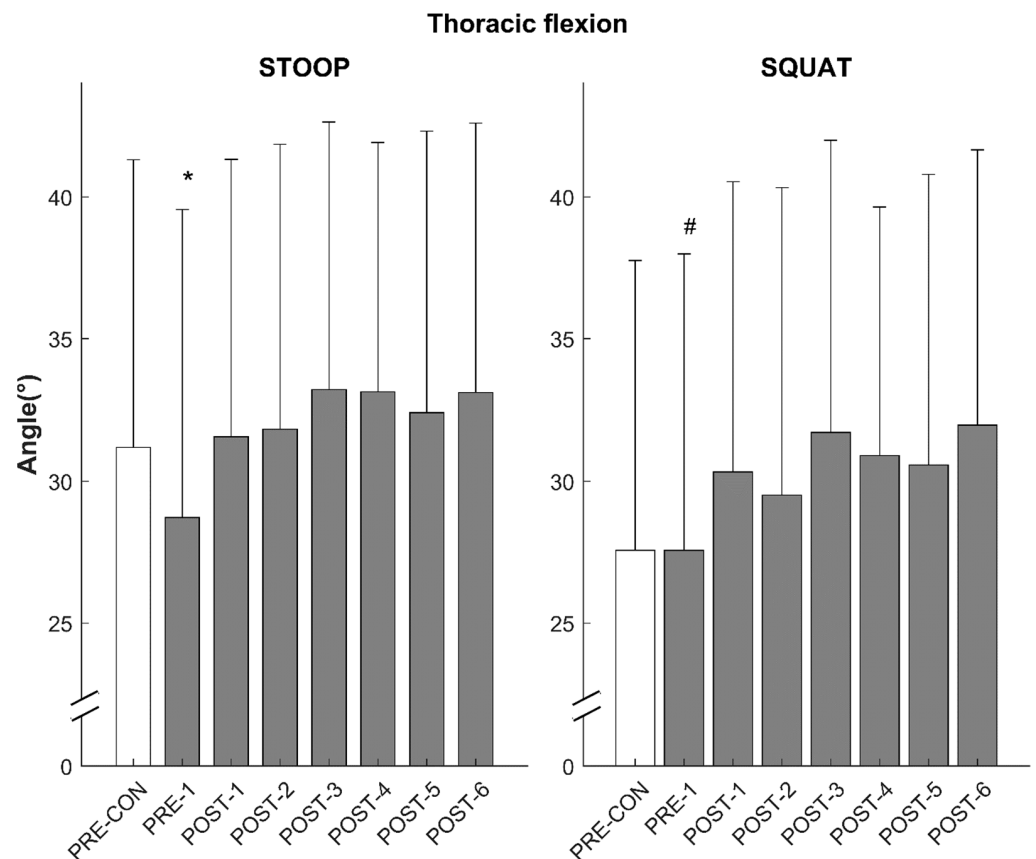


Figure 4. Evolution of mean (SD) thoracic flexion (°) in PRE-CON and over the familiarization protocol from PRE-1 to POST-6 for STOOP and SQUAT. * Statistically different from POST-3, POST-4, and POST-6 ($p < 0.05$). # Statistically different from POST-3 and POST-6 ($p < 0.05$).

Table 1. Mean (standard deviation) of lumbar, hip, and knee kinematics and smoothness in STOOP and SQUAT in PRE-CON and over the familiarization protocol from PRE-1 to POST-6.

		PRE-CON	PRE-1	POST-1	POST-2	POST-3	POST-4	POST-5	POST-6
Lumbar Flexion (°)	STOOP	33 (9.9)	33.4 (8.9)	33.2 (9.6)	32.5 (10.6)	30.8 (8.7)	31.8 (9.7)	32.9 (9.2)	31.8 (9.8)
	SQUAT	16.1 (10)	16.6 (9.5)	16.4 (9.6)	16.1 (11.9)	14.0 (9.7)	14.2 (12)	14.8 (9.6)	14 (11.6)
Hip Flexion (°)	STOOP	77.7 (11.7)	81.5 (10.8)	82.4 (12.4)	82.0 (9.2)	83.1 (10.2)	82.5 (10.3)	82.3 (10.5)	82.7 (11.6)
	SQUAT	94.8 (6.8)	96.5 (5.6)	94.3 (6.7)	94.8 (5.3)	96.2 (5.8)	95.3 (8.0)	94.0 (6.0)	95.8 (7.2)
Knee Flexion (°)	STOOP	17.3 (15.2)	21.0 (18.6)	21.4 (15.3)	20.9 (15.0)	20.6 (14.5)	20.2 (15.5)	20.7 (15.7)	21.3 (16.4)
	SQUAT	120.5 (19.4)	114.9 (19.0)	116.5 (17.0)	117.4 (17.8)	117.6 (18.7)	117.8 (16.5)	119.3 (15.1)	119.1 (14.4)
Smoothness	STOOP	−1.6 (0.1)	−1.6 (0.1)	−1.6 (0.1)	−1.5 (0.1)	−1.6 (0.1)	−1.6 (0.1)	−1.6 (0.1)	−1.6 (0.1)
	SQUAT	−1.6 (0.1)	−1.5 (0.1)	−1.5 (0.1)	−1.5 (0.1)	−1.6 (0.1)	−1.6 (0.1)	−1.6 (0.1)	−1.6 (0.1)

Table 2. Median (interquartile range) of confidence ellipse area and anteroposterior amplitude of postural oscillations in STOOP and SQUAT in PRE-CON and over the familiarization protocol from PRE-1 to POST-6. * Statistical main effect of the familiarization protocol.

		PRE-CON	PRE-1	POST-1	POST-2	POST-3	POST-4	POST-5	POST-6
Ellipse Area (mm ²)	STOOP *	1808 (234)	1820 (343)	1880 (371)	1895 (441)	1849 (266)	1825 (346)	1815 (197)	1835 (239)
	SQUAT *	2790 (1694)	2983 (1288)	3506 (1733)	3360 (988)	3444 (1126)	3327 (1612)	2977 (1535)	2805 (1296)
Antero posterior Amplitude (mm)	STOOP	90 (26)	85 (25)	88 (34)	99 (30)	82 (28)	92 (29)	86 (20)	91 (40)
	SQUAT	75 (24)	79 (26)	80 (19)	88 (25)	76 (21)	78 (16)	73 (30)	75 (16)

Neuromuscular parameters were only slightly influenced (Table 3). The Gluteus Maximus activity (ranging from $19.2 \pm 14.6\%$ for PRE-1 to $19.4 \pm 11\%$ for POST-6) for STOOP was altered over the familiarization protocol ($p = 0.043$, $W = 0.03$), without revealing further statistical effect after the post-hoc comparisons. Mean neuromuscular activities over the protocol for ES ($40.8 \pm 1.2\%$ and $43 \pm 2.2\%$ for STOOP and SQUAT, respectively), OE ($7.5 \pm 1.6\%$ and $6.4 \pm 0.6\%$), RA ($3 \pm 0.4\%$ and $2 \pm 0.2\%$), and TFL ($5.9 \pm 1.3\%$ and $13 \pm 10.8\%$) were not influenced by the familiarization, either for STOOP or SQUAT.

Table 3. Median (interquartile range) of muscle activity (RMS) in STOOP and SQUAT in PRE-CON and over the familiarization protocol from PRE-1 to POST-6. * Statistical main effect of the familiarization protocol.

		PRE-CON	PRE-1	POST-1	POST-2	POST-3	POST-4	POST-5	POST-6
Erector Spinae (RMS %)	STOOP	40.6 (12.4)	39.1 (12.4)	41.4 (11.8)	41.4 (8.7)	42.3 (12)	39.6 (10.4)	39.9 (10)	42.4 (10.4)
	SQUAT	41.7 (12.9)	40.9 (12.3)	45 (15)	47.4 (14)	43.3 (12.1)	41.4 (8.8)	41.3 (10.1)	43.6 (10.6)
Gluteus Maximus (RMS %)	STOOP *	19.5 (13.2)	19.9 (14.6)	25.2 (13.9)	19.8 (10.4)	19.6 (9.2)	20.7 (10.1)	19.5 (12.1)	19.4 (11)
	SQUAT	19.5 (11.6)	21.4 (12.5)	27.2 (12.2)	22.7 (11.3)	22.4 (10.2)	23 (9.9)	21.7 (10.8)	21.4 (9.8)
Obliquus Externus (RMS %)	STOOP	5 (4.6)	6.3 (6.3)	10.1 (9.4)	8.9 (5.7)	7.9 (6.1)	7.2 (5.1)	7.6 (8.1)	6.9 (6.2)
	SQUAT	6 (2.9)	5.3 (3.2)	7.1 (5)	6.7 (3.8)	6.6 (4.3)	6.6 (3.9)	6.4 (3.5)	6.8 (3.8)
Rectus Abdominis (RMS %)	STOOP	3.1 (2.6)	2.8 (1.7)	2.6 (1.6)	3.4 (3.4)	2.8 (2.6)	2.6 (2.3)	3.1 (3.6)	3.6 (4.1)
	SQUAT	2.1 (1.4)	2 (1.4)	1.9 (1.1)	2.2 (1.5)	1.9 (1.2)	1.8 (1.1)	1.8 (1)	2.3 (1.5)
Tensor Fascia Latae (RMS %)	STOOP	7.3 (7.9)	8.2 (13.3)	5.5 (3.2)	5 (3)	4.9 (2.6)	5.6 (3.1)	5.9 (3.8)	4.5 (3.1)
	SQUAT	11.9 (12.0)	12.4 (11.7)	13.3 (13.2)	12.2 (13.1)	11.8 (12.7)	11.3 (12.2)	11.7 (11.9)	11.7 (12.6)

NASA-TLX global scores were not influenced by the familiarization protocol, whatever the technique used, with mean scores ranging from 119 to 133 for STOOP and from 121 to 152 for SQUAT. Nevertheless, the statistical analysis demonstrated a main effect on mental demand in SQUAT ($p = 0.03$, $W = 0.11$). Pairwise comparisons showed that POST-6 (2 ± 2) was lower than PRE-1 (3.5 ± 2.75), suggesting that stabilization could occur after POST-6. Wilcoxon's tests showed that PRE-CON (2 ± 2.75) was not different from PRE-1 ($p = 0.07$)

nor from POST-6 ($p = 0.5$). Other NASA-TLX weights were not significantly influenced by the familiarization protocol.

Pressure perceptions, evaluated through Likert scales, were influenced by the familiarization protocol (Figure 5 and Table 4). Statistical analyses showed a significant main effect of familiarization on knee perceived pressure for both STOOP ($p < 0.001$, $W = 0.19$) and SQUAT ($p = 0.01$, $W = 0.21$). For STOOP, pairwise comparisons revealed that perceived pressure in POST-1 and POST-2 was significantly higher than in POST-5 and POST-6 ($p < 0.001$). For SQUAT, this analysis revealed significantly higher perceived pressure in PRE-1 than in POST-4 to POST-6 ($p < 0.01$), as well as for POST-1 compared to POST-4 and POST-6 ($p < 0.001$). PRE-CON values were not assessed due to the obvious absence of pressure perception. Also, there was a significant main effect of familiarization on buttock perceived pressure for both STOOP ($p < 0.001$, $W = 0.23$) and SQUAT ($p = 0.01$, $W = 0.13$). For STOOP, pairwise comparisons revealed that buttocks perceived pressure was significantly higher in PRE-1 than in POST-4 to POST-6 ($p \leq 0.001$), and also significantly higher in POST-1 than in POST-5 and POST-6 ($p < 0.001$) and higher in POST-2 and POST-3 than in POST-6 ($p \leq 0.001$). For SQUAT, buttocks perceived pressure was significantly higher in PRE-1 than in POST-3 and POST-6 ($p < 0.01$). Then, there was a significant main effect of familiarization on armpit perceived pressure in STOOP ($p = 0.01$, $W = 0.13$; Table 4), but post-hoc tests could not tease out significant differences between sessions. Next, the statistical analysis showed a significant main effect of familiarization on trapezius pressure in STOOP ($p = 0.009$, $W = 0.13$), which was higher in PRE-1 than in POST-6 ($p < 0.01$). Finally, pressure perceptions at armpits and trapezius levels in SQUAT, as well as back muscle exertion perception in both STOOP and SQUAT, were not significantly influenced by the familiarization protocol (Table 4).

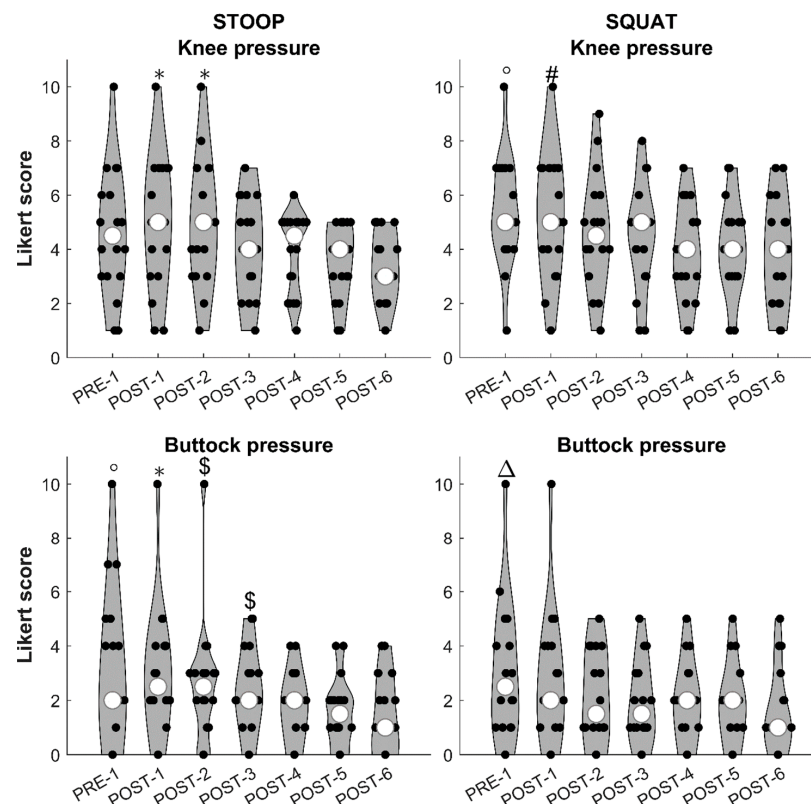


Figure 5. Evolution of median (white dot) and distribution (black dots) for knee and buttock pressures in STOOP and SQUAT. ° statistically different from POST-4, POST-5, and POST-6. Δ Statistically different from POST-3 and POST-6. # Statistically different from POST-4 and POST-6. * Statistically different from POST-5 and POST-6. \$ Statistically different from POST-6.

Table 4. Median (interquartile range) of armpits and trapezius pressure in STOOP and SQUAT in PRE-CON and over the familiarization protocol from PRE-1 to POST-6. * Statistical main effect of the familiarization protocol.

		PRE-1	POST-1	POST-2	POST-3	POST-4	POST-5	POST-6
Armpits	STOOP *	1.5 (3.75)	1 (3.75)	2 (3)	1.5 (2.75)	1.5 (2)	1 (1.75)	1 (2.75)
	SQUAT	1 (4)	1 (3.25)	1.5 (2.75)	1 (1.75)	1 (1.75)	1 (1.75)	1 (2.5)
Trapezius	STOOP *	2 (3.75)	2 (3.75)	2 (2)	1.5 (2)	1.5 (1)	2 (1)	1 (1)
	SQUAT	2 (2)	2.5 (3)	2 (1.75)	1 (2)	2 (1.75)	2 (1)	1 (1)
Back muscle Exertion	STOOP	2 (1)	2 (1)	2.5 (1.75)	2 (2)	2 (0.75)	2 (1.75)	2 (1.5)
	SQUAT	1.5 (1)	2 (2)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)

The ANOVA showed a significant main effect of familiarization on PRECI ($p < 0.001$, $\eta^2 = 0.34$) (Figure 6). Post-hoc comparisons revealed that the performance time during PRE-1 was higher than for all other conditions ($p < 0.001$). POST-1 and POST-2 were also higher than POST-4, POST-5, and POST-6 ($p \leq 0.001$). Finally, POST-3 was significantly greater than POST-5 and POST-6 ($p < 0.05$). Student's *t*-tests showed that PRE-CON (42.2 ± 8.2) was not different from PRE-1 ($p = 0.9$) but was higher than POST-4 ($p < 0.001$).

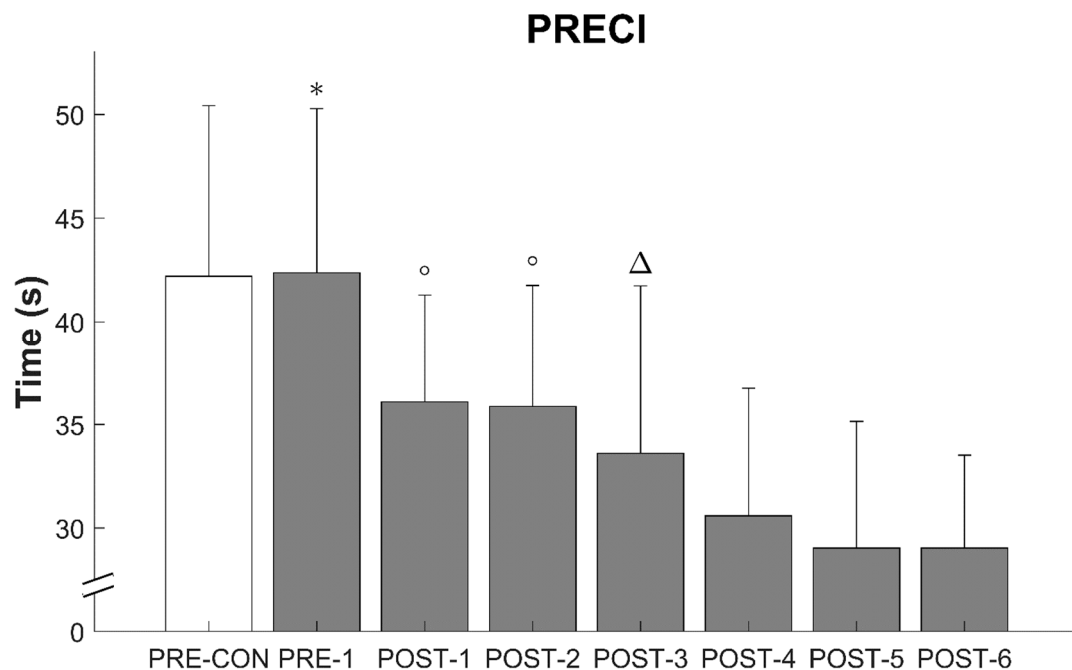


Figure 6. Evolution of mean (SD) performance time in PRE-CON and over the familiarization protocol from PRE-1 to POST-6 for PRECI. * Significantly different from POST-1 to POST-6. ° Significantly higher than POST-4 to POST-6. Δ Significantly higher than POST-5 and POST-6.

4. Discussion

The primary findings of this study were that (i) thoracic kinematics, contact pressure perception and performance changed across the familiarization protocol, and (ii) thoracic kinematics, contact pressure perception and performance reached a steady state after the third or fourth session of the familiarization protocol.

Back curvature, pressure perceptions, and performance changed over the familiarization protocol with the soft back-support exoskeleton prior to reaching a steady state. Indeed, thoracic flexion stabilized after session 3 in both STOOP and SQUAT. This might suggest that thoracic kinematics is changing to adapt to the exoskeleton constraints provided by the elastic bands along the back and buttocks and attached to the shoulders and to the knees. In addition, pressure perceptions in STOOP and SQUAT at knee and buttocks levels were also influenced by the familiarization protocol and reached a steady state after sessions 3 or 4, depending on the task and the pressure zone. Armpits and trapezius perceived pressures were also influenced by the familiarization protocol. These changes in perceived pressure of the exoskeleton might be a sign that participants felt increased comfort after several uses, which might speak in favor of a better acceptability of the exoskeleton. Interestingly, pressure regions that were most influenced by the familiarization protocol referred to the lower limb (buttocks and knees), while kinematic variations were located at the thoracic spine. Despite the variety of measurements, it appears that there was no evolution after session 4 for any variable. The performance time measured with PRECI stabilized after session 4 compared to their first use of the exoskeleton, suggesting that participants get more accurate after they get familiar with the exoskeleton. Overall, this suggests that a soft back-support exoskeleton familiarization model is characterized by a change in motor behavior, followed by its stabilization after the third or fourth familiarization session. Such changes, followed by a stabilization, have already been observed in the literature by Galle et al. (2013) [14] and Panizzolo et al. (2019) [13] with walking exoskeletons. As a comparison, Panizzolo et al. (2019) [13] found that 3 sessions of 20 min induced a stabilization of metabolic cost changes when using a hip exoskeleton during walking, while Galle et al. (2013) [14] found that metabolic cost stabilized after the first 18.5 min of walking with an ankle exoskeleton. Thus, the type of exoskeleton (back, hip, or ankle) and tasks (lifting or walking) appear to influence the familiarization time. But the overall model of this familiarization remains comparable, with an evolution of the parameter after the introduction of the exoskeleton followed by a stabilization, whatever the studied (biomechanical or physiological) variable. This familiarization model is somehow also in line with Shadmehr & Mussa-Ivaldi (1994) [15], who observed motor changes followed by a return to the initial pattern when handling a specific manipulandum, designed to evaluate the evolution of the motor behavior when exposed to multiple new tasks.

Other variables, such as postural stability and, to a lesser extent, NASA-TLX, were influenced by the exoskeleton, but the results did not verify our hypotheses, as no clear model emerged from these measurements. Indeed, postural oscillations decreased in POST-6 compared to POST-1 and POST-2 but not in PRE-1. It is possible that postural stability improves after the familiarization protocol, mitigating the acute postural stability effects observed by Theurel et al. (2018) [11], who reported impaired postural stability when using an upper limb exoskeleton. Task load perception did not change across the familiarization protocol. Only mental demand decreased from PRE-1 to POST-6, suggesting that participants obtained mentally habituated to the exoskeleton when performing the task. Accordingly, global task load perception while wearing the exoskeleton would not be sensitive to familiarization and could be evaluated without previous habituation. Previous studies reporting a diminution of task load perception while using upper limb exoskeletons [37,38] would not suffer from this lack of familiarization issue. Lumbar flexion, hip flexion, and knee flexion, as well as muscular activity, were not influenced by the familiarization protocol, suggesting that there was no motor behavior adaptation for these variables.

Put together, these results suggest that it will be desirable to familiarize participants during 4 familiarization sessions of 1 h duration to stabilize their motor control and exoskeleton perception. Moreover, results suggest that measuring the effect of the exoskeleton during the early stage of use can lead to misestimating its long-term effects because of changes that appear during the familiarization protocol. For instance, while measuring thoracic flexion in STOOP and SQUAT, comparing PRE-CON to PRE-1, as it is usually car-

ried out in the literature, did not show the same result as comparing PRE-CON to POST-3. So, ignoring the familiarization period could lead to a back curvature measurement that is not representative of long-term motor behavior, mitigating the acute effects observed, for example, by Ulrey and Fathallah (2013) [9]. As for thoracic flexion, the performance times measured with PRECI in PRE-1 and POST-4 were not giving the same result if compared to PRE-CON. So, measuring in the early stages of exoskeleton use might lead to a misestimate of the long-term performance time.

In the present study, measurements were carried out at the end of sessions lasting 1 h. It is worth noting that Lee (2019) [39] described a decrease in motor performance between the end of a session and the beginning of the following session. Thus, in the present study, one can reasonably speculate that participants lose a part of their familiarity with the exoskeleton between each session. Future work should determine the smallest duration per session inducing the same effects and quantify the retention between the end of a session and the beginning of the following one. This would help optimize the time spent during the familiarization protocol. Also, our results suggest that there are only slight differences between STOOP and SQUAT in terms of familiarization duration or variables of interest. The familiarization with the exoskeleton seems to affect both tasks in the same manner, even if the exoskeleton was originally designed to primarily help workers during STOOP. Thus, the present results may be transferred to other soft-back exoskeletons with comparable assistance designs. However, we can not speculate on the familiarization model when using active exoskeletons because of their large differences regarding assistance management.

Limitations

As women were not evaluated in the present study, our results cannot be generalized to all workers. Accordingly, this research question would need to be addressed for women in the future. For that purpose, the present work provides a relevant framework to optimize the experimental protocol in terms of the number of familiarization sessions and the types of variables to characterize motor behavior. In addition, a control group was lacking in the present study. This would have helped to further characterize these motor behavior changes during the familiarization of the exoskeleton. Some variables (postural stability, muscle activity) were influenced by the familiarization protocol, but post-hoc tests failed to demonstrate differences between conditions. This can be explained by the weak effect size (e.g., $W = 0.03$ for Gluteus Maximus activity in STOOP). The exoskeleton did not alter the performance in PRE1 and led to a great enhancement of performance across sessions. It is possible that participants were not totally familiar with this challenging task, despite the task habituation protocol, and that the familiarization protocol allowed them to further enhance their performance. Therefore, future use of this task will make sure that participants stabilize their performance before introducing such variables within a familiarization protocol. Another limitation is that our results are based on mean values, and some individuals may take more time to become familiar with the exoskeleton. Finally, measurement errors due to soft tissue artifacts, markers and electrode placements across sessions, and EMG crosstalk could bias the present results. However, to ensure reproducibility and consistency of marker and electrode placements, pictures were systematically taken during the participant's preparation. Therefore, these errors could be considered relatively small compared to the observed differences.

5. Conclusions

The present study is the first to evaluate the familiarization time needed prior to an optimized use of a soft-back exoskeleton. According to our results, future studies will have to incorporate a significant amount of time to familiarize participants with the exoskeleton in order to avoid any misestimation of the outcomes. More specifically, to ensure familiarization with the CORFOR[®] occupational soft back-exoskeleton, four sessions of 1 h duration are recommended. This would place users in a steady state in terms of

motor behavior (thoracic flexion, pressure perception, and performance), allowing them to take advantage of the benefits of such an assistive device. However, these results are based on mean values, and some individuals may take more time to become familiar with the exoskeleton. As the perceived pressure evaluation carried out by the participants also stabilized after the fourth session, it could be an affordable and practical way to ensure proper familiarization with the exoskeleton based on this parameter. Thus, we recommend evaluating the perceived pressure at the main contact points between the exoskeleton and the user (e.g., knee and buttocks for the CORFOR[®]) during the familiarization and waiting until it stabilizes.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical regulations.

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