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Exploring the Influence of Structured Familiarization to an Adjustable, Passive Load-Bearing Exoskeleton on Oxygen Consumption and Lower Limb Muscle Activation During Walking

Gabriel Diamond-Ouellette, Miorie Le Quang, Thomas Karakolis, Laurent J. Bouyer, and Krista L. Best

***Abstract*—Walking patterns is modified during load carriage, resulting in an increased activation of lower limb muscles and energy expenditure. Negative effects of load carriage could be minimized by wearing an exoskeleton, but evidence on the effects are conflicting. The objectives of this study were to describe the influence of an adjustable, passive load-bearing exoskeleton on the metabolic cost of walking (MCW) and associated muscle activations, and to explore changes in MCW after a familiarization process. Thirteen participants walked on a treadmill with a 22.75 kg payload at six preselected speeds (from 0.67 to 1.56 m/s) under three walking conditions: 1) without exoskeleton (NoExo); 2) with exoskeleton before familiarization (ExoPre); and 3) with exoskeleton after familiarization (ExoPost). Metabolic data was normalized to walking speed to provide MCW. Multi-muscle surface electromyography (EMG) was time and amplitude normalized to the gait cycle to provide muscle activation patterns. The familiarization occurred over three weeks including exposure to the exoskeleton. Differences in MCW and muscle activations were compared using a nonparametric analysis of longitudinal data. There were statistically significant increases in MCW for all speeds in the ExoPre and ExoPost conditions compared the NoExo. The average muscle activation showed an increase during ExoPre and ExoPost for the three speeds evaluated. Post-hoc analysis showed no significant effect of the familiarization period on metabolic data. In conclusion, a first exposure to the adjustable exoskeleton increased MCW and muscle activations, but the familiarization process did not provide any benefits toward a reduction in MCW or reduction in muscle activations at all speeds evaluated.**

***Index Terms*—Passive exoskeletons, Metabolic expenditure, Electromyography, Motor learning, Assistive devices, load carriage.**

I. INTRODUCTION

EFFICIENT walking occurs when there is an optimal energy transfer between the lower limbs during step-to-step transition [1], described as the inverted pendulum principle [2], [3]. Optimized gait patterns (e.g., spatiotemporal foot fall parameters) reduce physical responses, such as the metabolic cost of walking (MCW) (i.e., energy expenditure) and muscle activation levels [4], [5].

However, load carriage during walking (e.g., wearing backpacks for hiking, or fragmentation vests for military or law enforcement tasks) alters gait biomechanics and disrupts physiological responses [6]. Previous studies have demonstrated the influence of load carriage on several gait parameters. For example, carrying a backpack under four load conditions during a controlled walking task resulted in decreased step length, increased stride frequency and time in double support [7], and reduced stance duration [8]. Grenier et al., (2012) evaluated the effects of load carriage during walking, and observed significant alterations in spatiotemporal gait parameters under two load conditions (i.e., 27.2 % and 46.1% of body mass) [9]. Bode et al., (2021) suggested that increasing the time in double limb support when carrying loads may facilitate control and stability during walking [10]. Previous studies during overground walking described an increase in knee flexion angle during stance with increasing load as a way to increase stability [8], [11]–[14].

Although these alterations in gait patterns and kinematics may reduce the risk of injury during prolonged load carriage

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Ethics Review Board of the CIUSSS-CN under Application No. 2018-438, and performed in line with university requirements.

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[11], optimal energy transfer and optimal muscle activation may be disrupted [15]. For example, increased knee flexion during weight acceptance facilitates absorption of impact forces [11] but requires increased activation from the rectus femoris and vasti muscles [16]–[18] leading an increase in metabolic cost of walking [19]. Increased muscle activity is associated with increased metabolic costs [17]. Indeed, studies on treadmills with load carriage conditions ranging from 0% to 70% of body weight reported a linear increase in the metabolic response [14], [20]. Walking under these conditions also leads to an earlier onset of muscle fatigue [21] and increased risk of fatigue-related musculoskeletal (MSK) injuries over time [22].

Load-bearing exoskeletons have been targeted as a promising approach for reducing risk of MSK injury by lessening the impact of load carriage on gait biomechanics and physiological responses. Recent research on active and passive exoskeletons reported that reductions in the metabolic cost of walking is possible [23]–[26]. Contrary to active exoskeletons that improve endurance and reduce fatigue, passive load bearing exoskeletons offer less biomechanical and physiological advantages. However, their reduced weight allows for greater mobility of the soldiers, an important element for military operation. For example, in our earlier study on customized passive load-bearing exoskeletons with three soldiers, we observed reduced energy expenditure while walking in a laboratory setting after a familiarization period. In this study, participants received 3 hours of familiarization over 9 days, which was associated with the observed reduction in energy expenditure [23]. Some principles of motor learning were followed in this study (i.e., variability of practice to enhance learning [27]). However, other important principles of motor learning (e.g., distribution of practice, progression, feedback) had to be omitted due to time constraints.

The two objectives of the current study were to 1) explore the influence of an adjustable passive load-bearing exoskeleton on MCW and muscle activation 2) explore changes in MCW and muscle activation after a familiarization period in healthy individuals.

We hypothesized that 1) the initial use of the passive load bearing exoskeleton will increase the MCW and muscle activation and, 2) after a period of familiarization, the MCW and muscle activation would return to baseline levels.

II. METHODS

A. Participants

Using a convenience sampling method, participants were recruited from the manufacturer of the exoskeleton to facilitate recruitment during the COVID pandemic (Male = 12, Female = 1). To be eligible for this study, participants were: 1) older than 18 years old without any self-reported neurological, metabolic or musculoskeletal injuries limiting load carriage and walking; 2) naïve to wearing the adjustable exoskeleton and to the tasks (never wore the adjustable exoskeleton); 3) at least “moderately active” or “active” on the self-reported Godin Leisure- Time Exercise Questionnaire [28]; and 4) “operationally fit” according to the Fitness for Operational Requirements of Canadian Armed Forces Employment (FORCE) evaluation which evaluates the minimum physical employment standard related to common defence and security duties through four components (20-metre rushes, sandbag lift, intermittent loaded shuttles and sandbag drag). Selected participants completed a two-week load carriage training phase to familiarize with the tasks, and were excluded if they were unable to walk with at least 22.75 kg during a one-hour period.

The local Research Ethics Board approved this study and informed consent was obtained from all participants (CIUSSS-CN #2018-438).

B. General Protocol

Prior to testing, sociodemographic information was obtained from each participant (i.e., age, sex, weight, height), as well as the Godin Leisure-Time Exercise Questionnaire [28]. If a participant scored adequately to the questionnaire, and passed the FORCE evaluation, they proceeded to complete a two-week load carriage familiarization with up to 22.75 kg load (Canadian army backpack (16.4 kg) and a fragmentation vest (6.35 kg)) without the adjustable exoskeleton (approx. 10 kg) and regardless of their body weight. Given participants were healthy civilians, the local Research Ethics Board recommended a maximal load of 22.75 kg. The overall testing protocol is schematically presented in Fig.1. Testing took place over three one week-long phases with a familiarization period to the adjustable exoskeleton. The first phase of this study was the selection of the participants. Phase 2 included a control condition where the participants had to walk with a load of 22.75 kg without wearing the exoskeleton (NoExo). During the second week, the participant had to walk with a load of 22.75 kg with the exoskeleton and before the familiarization period (ExoPre). Phase 3 involved walking with the 22.75 kg load while wearing the exoskeleton, but after a period of familiarization (ExoPost). Between phases 2 and 3, a three-week familiarization period with the exoskeleton was given to each participant.

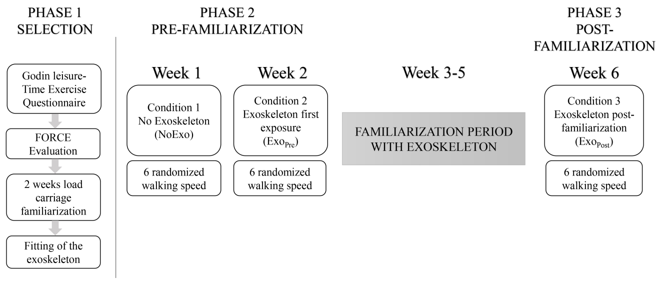

Fig. 1. Diagram representing the selection process, every condition and phases of testing.

For each testing session, participants were instructed to 1) stand still for 10 minutes to collect the oxygen consumption (VO2) in ml at rest (VO2REST) while electromyography (EMG) data collection started at min 9 to have one minute of baseline standing EMG for signal quality assessment. 2) Walk on a motorized treadmill (Horizon) until they reach a steady state VO2 in ml (VO2SS; at least 10 min); and 3) rest sitting on a chair without equipment until VO2 rest

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returned (approx. 15-20 min). This sequence was repeated for each of the walking speeds. The resting period allowed to test all six speeds on a given day. Participants walked at six preselected and standardized speeds (0.67 m/s to 1.56 m/s with an increment of 0.18 m/s) on a treadmill. Speed order was randomized for each participant and each experimental condition (i.e., NoExo, ExoPre and ExoPost). All speeds tests were done on the same day, in the morning. Total test time was approximately 3-4 hours.

C. Adjustable Exoskeleton

The fully adjustable passive load-bearing exoskeleton prototype (UPRISE Gen 4.0) developed by a Canadian company (Mawashi science and technology, Montreal, Canada), weights on average 10 kg and was developed to provide load transfer capacity in static and dynamic conditions. Contrary to the previous version [23], this iteration of the exoskeleton was adjustable instead of customized to each participant but remained based on the same biomechanical principles. Minor changes in design were implemented to provide maximum adjustability to different participants' anthropometry and to improve joint mobility and range of motion. These modifications are as follows: 1) Imitating the human hip joint by integrating a ball and socket joint under the rail mechanism of the exoskeleton (instead of the previous four-bar mechanism); 2) Removing the medial knee mechanism (and maintaining only the lateral one to reduce risk of tripping previously caused by potential inter-leg contact); 3) Redesigning the spine (now a double spine) to provide more support and reduce the scoliosis effect observed in the previous iterations; 4) Integrating an adjustable tilting sacrum to improve users' range of motion (ROM) during trunk flexion; 5) Improving the ankle mechanism to reduce user discomfort and optimize fitting. The adjustment process included taking measurements of the participant lower limb segments (e.g., thigh and shank length, etc.) in order to select the exoskeleton part size based on anatomical measurement of this participant (e.g., thigh rod ranging from 20 mm to 130 mm long). A human factors specialist who works at the exoskeleton maker assembled and fitted the exoskeleton on the participant, and noted any discrepancy between the anatomical joint and the device joint (i.e., height, angle and rotation). When all joints were aligned correctly, the participant was allowed to perform minimal movements to provide feedback on mobility and comfort. As needed, one or multiple parts of the exoskeleton were changed or adjusted in order to have maximal acceptance of the device (i.e., minimized discomfort from the user). Fig. 2 shows the exoskeleton main component and multiple subsections that account for the adjustability.

D. Familiarization to the Exoskeleton

The familiarization period was based on some of the principles of motor learning and consisted of a total of 14 days of controlled tasks performed with the exoskeleton (between 1h to 1h30m) and occurred over three to four weeks. An evaluator (the principal investigator) was in charge of setting up the familiarization period ensuring participants were adequately introduced to the key concepts and procedures. The familiarization period included distributed practice by incorporating a day of rest period between days of training. Variability of training was introduced by incorporating different exercises each day and dividing the familiarization period into three phases of different types of activities. The familiarization period also featured a gradual progression in both loads carried and difficulty of the task (i.e., an increase in difficulty was possible if the participant was able to perform the task without errors or if their fitness level allowed it). Phase A included loaded marches while carrying 12 kg over 30 minutes. Phase B involved using a loaded standardized dynamic course (e.g., agility drill, stairs with load, jerry can run, etc.) and also included loaded marches, with an increase in weight and distance. Phase C integrated the previous phases but also added a task-oriented course recommended for soldiers (e.g., walking while "engaging target," rush to prone, etc.). Each phase was also designed to last a number of session or percentage of the familiarization time (Phase A = 20%, Phase B and C = 40% respectively). Participants needed to change phase based on the time allowed, but could adapt the difficulty of the tasks based on their fitness level. This task-oriented course was inspired by the Canadian Load Effects Assessment Program (CAN LEAP), which included more realistic combat tasks [29]. Intrinsic feedback was obtained by the learner during the activities (e.g., sensory feedback during agility ladder drills), and extrinsic feedback was provided at the end of each activity by the evaluator on the performance. The evaluator also offered verbal information on how to perform the activities during Phase A and reduced the information given during Phases B and C. All phases and activities required the participant to at least don and doff, learn to adjust, and assemble the exoskeleton, complete light activities for warm-up (e.g., side shuffle, bear crawl, etc.), and perform muscle activation exercises (e.g., walking lunges, banded lateral walk, etc.).

E. Instrumentation

A portable metabolic gas analyzer (COSMED K5, Rome, Italy) was used to measure the breath-by-breath respiratory gas exchange, which is mainly oxygen consumption (VO2) and carbon dioxide output (VCO2). After an initial warm-up of 60 minutes, the K5 was calibrated according to the manufacturer's instructions. This device has shown to be reliable [30] and accurate at a wide range of intensity [31]. Muscle activity was recorded using wireless surface EMG sensors (Trigno, Delsys Inc, Boston, MA, USA) at a sampling rate set at 1926 Hz/muscle. Skin preparation and sensors placements were performed according to the SENIAM recommendations, with slight modification in sensor placement if the location was not accessible due to the presence of an exoskeleton part [32]. Sensors placements were marked with a medical skin marker to ensure the same sensor placements for the ExoPre and ExoPost conditions. The following muscles were recorded bilaterally: Rectus Femoris (RF; hip flexor/knee extensor), Vastus Medialis (VM; knee extensor), Semitendinosus (ST; hip extensor/knee flexor), Medial Gastrocnemius (MG; ankle plantarflexor/knee flexor) and Soleus (SOL; ankle plantarflexor).

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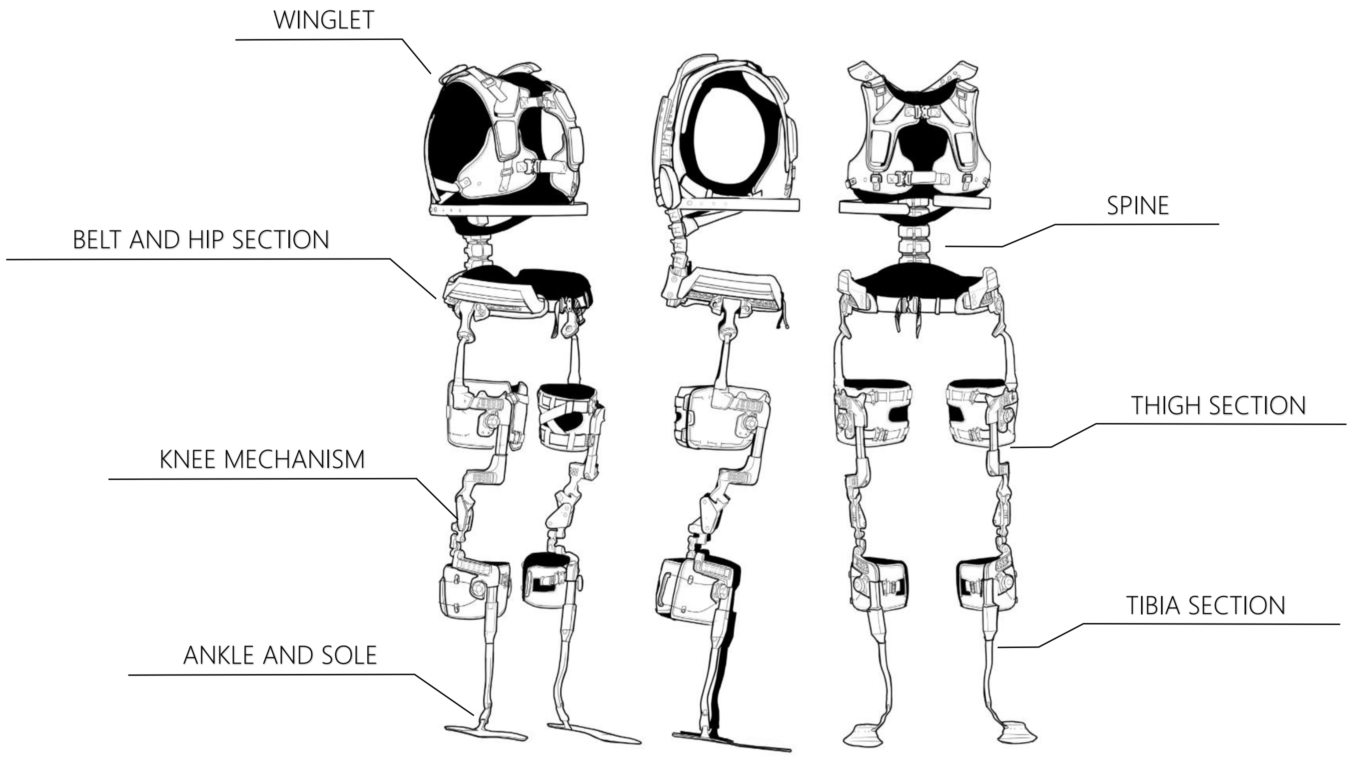

Fig. 2. Main component of the adjustable exoskeleton from three different angles.

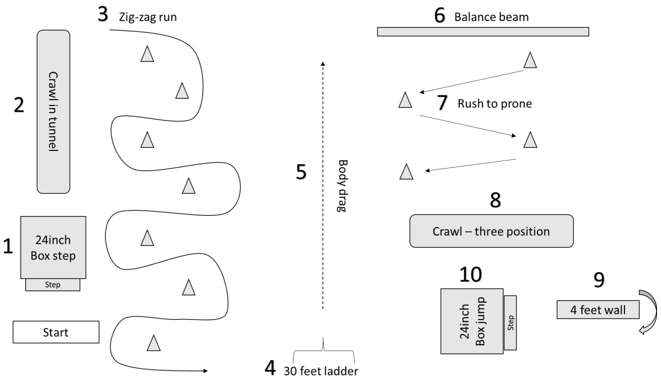

Fig. 3. The familiarization period. Phase C includes a obstacle course based on the CAN LEAP .

F. Data Processing

Equation (1) shows the net MCW for each gait speed and experimental condition was estimated to be the difference between the measured rate of oxygen exchange (VO2) during quiet standing and walking and transformed into joules. The VO2 rate was normalized to participant total mass, including the exoskeleton when applicable and walking speed [33].

$$MCW(J\cdot kg^{-1}\cdot m^{-1}) = \frac{VO2_{SS}-VO2_{REST}}{Weight(kg)*Speed(m\backslash s)} \tag{1}$$

EMG signals for the slowest, middle, and fastest speeds achieved by all participants (i.e., 0.67 m/s, 1.03 m/s and 1.39 m/s) were analyzed in this study. EMG data were band-pass filtered off-line at 40-450 Hz using a fourth-order zero-lag Butterworth filter; and then rectified (root mean square (RMS); non-overlapping rectangular window length of 0.10 s), cut into individual gait cycles using the inertial sensor of the EMG. The EMG signals of each muscle were then segmented into their activation timing periods, where 0% represents the initial heel strike, and 100% represents the next heel strike [34].

- RF was analyzed between 0% and 10%, and also between 40% and 70% (RF – 0% - 10%; RF – 40% - 70%);
- VM was analyzed between 0% and 20%, 20% and 40% and also between 80% and 100% (VM – 0% - 20%; VM – 20% - 40%; VM – 80% - 100%);
- ST was analyzed between 0% and 20% and also between 70% and 100% (ST – 0% - 20%; ST – 70% - 100%);
- MG was analyzed between 0% and 50% (MG – 0% - 50%);
- SOL was analyzed between 10% and 50% (SOL – 10% - 50%).

The data were then normalized to the amplitude across conditions. To do so, the peak amplitude of activation of each muscle was located for every gait section in the different walking conditions, and was then normalized in regards of the peak activation found in the NoExo condition. All data were processed with custom algorithms developed in Matlab (Matworks Version R2019b).

G. Analysis

Sociodemographic information and Godin Leisure-time and FORCE scores were summarized (mean, standard deviation). Metabolic data was analyzed using a nonparametric analysis

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of Longitudinal Data (nparLD) (package nparLD, version 2.1, R software; [35], which was specifically designed for ordinal variables with nonparametric distributions that may change across conditions. As a rank-based analysis of variance, the nparLD procedure is robust with regards to outliers and small sample size. Exceptional for a nonparametric analysis of variance, nparLD produces effect size estimations, named relative treatment effects (RTE) that are proportional to Cohen's d with simulated data suited for Cohen's d. As there are two independent variables for the metabolic data (i.e., testing conditions and speeds), the statistical model used was LD-F2 which refers to the experimental design with two subplot factors (i.e., longitudinal data for one group of subjects and a structure in the time where speeds are the stratification of testing conditions) [36]. In these comparisons, the RTE values vary between 0 and 1, with 0.5 as the null hypothesis and effect sizes considered small, medium or large for RTE values over 0.56, 0.64 and 0.71 or below 0.44, 0.36 and 0.29, respectively [37]. The ANOVA-type statistic (ATS) from the nparLD provides a robust estimate of differences within repeated discrete data. A subjective rating of whether familiarization worked (ie. binary reponse; yes/no) was made through visual observation of the MCW curve and was considered 'yes, it worked' if 1) the MCW of at least three walking speeds and the mean MCW for all walking speeds in the post familiarization condition was below the MCW in the pre-familiarization condition. Regarding muscle activation, as data variability differed across muscles, a visual analysis of variance was used [38]. Briefly, a 95% CI around the mean of the NoExo condition was established separately for each muscle recorded. Significant change was establish if the mean EMG signals of the ExoPre and ExoPost conditions were outside of this confidence interval (CI).

III. RESULTS

Thirteen employees of the exoskeleton manufacturer participated in the study (12 males; mean (standard deviation) age was 33.5 (7.2) years; mean (standard deviation) height was 175.6 (6.4) cm; and mean (standard deviation) weight was 71.0(8.0) kg). Table 1 shows the Godin Leisure-Time and the FORCE evaluation scores, as well as the subjective rating of whether familiarization worked (yes, no). After familiarization, six out of 13 participants had a lower MCW compared to ExoPre that was observed by the mean MCW or the MCW at individual walking speeds.

A. Metabolic Cost of Walking

There was a statistically significant change in MCW between conditions [ATS(1.90) = 20.54 ; $p < 0.001$] as shown in Fig. 4. There was an increase in MCW with first exposure to the exoskeleton (ExoPre), which remained after familiarization (ExoPost) compared to NoExo condition to all speed evaluated. Post hoc analysis showed significant difference between NoExo and ExoPre [ATS(1.00) = 26.78 ; $p < 0.001$] and NoExo and ExoPost [ATS(1.00) = 33.58 ; $p < 0.001$], but no difference between ExoPre and ExoPost conditions [ATS(1.00) = 0.09 ; $p = 0.76$] at all walking speeds. Individual change in MCW can be found in supplementary file.

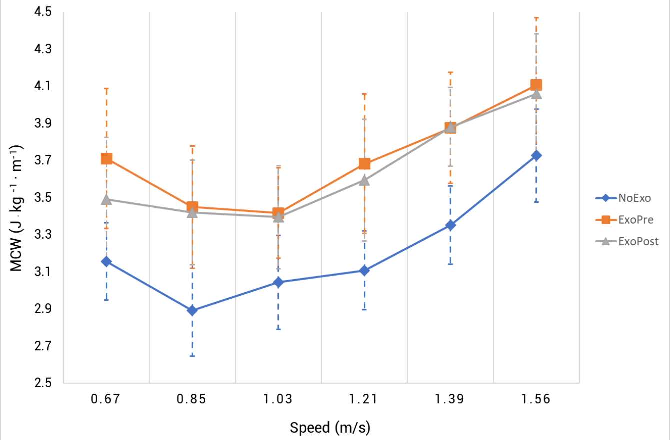

Fig. 4. The Metabolic Cost of Walking (MCW) presented by condition (NoExo; ExoPre; ExoPost) and speeds with the 95% confidence interval.

B. EMG data

Mean muscle activations and 95% CI are graphically presented in Fig. 5. There was a difference in muscle activations between conditions at all three speeds analyzed. Overall, this difference was symmetrical and similar across speeds, occurring mainly in muscles controlling the knee joint (RF – EndSt, VM – Load, VM – MidSt, VM – TSw and ST - TSw). Specifically, these differences are increases in muscle activations. In addition, plantarflexor muscles showed mostly no statistical change across conditions (n=34/36) except in two instances where an increase in muscle activation was observed in the right MG and SOL at 1.39 m/s. Finally, there were two cases of a significant reduction in muscle activations when participants wore the exoskeletons (right MG – Stance at 0.67 m/s and 1.39 m/s).

IV. DISCUSSION

In contrast to the preliminary findings with the customized load-bearing exoskeleton (UPRISE GEN 3.0) where an improvement in MCW after a period of familiarization was observed in 3 military personnel [23], the current findings doesn't support our initial hypothesis and suggest that familiarization with an adjustable exoskeleton did not decrease the MCW in a small sample of physically fit adults. The literature suggests that integrating the principles of motor learning into a familiarization period is important to enhance motor learning and to increase retention and transfer of new motor skills into another context [27], [39]–[41]. Therefore, It was surprising to observe significant variability in the changes in MCW among participants. While six participants experienced reduction (small or significant) in MCW, others experienced an increase, and some remained unchanged. To aid in the interpretation of these findings, we have generated potential explanations that may explain our results.

The initial increase in the MCW with a full-body or quasi-passive exoskeleton were similar to previous results [42], demonstrating a difference in the increase in MCW during the first exposure to the exoskeleton . However, the MCW increased by 8.0% in the previous study compared to 15.5%

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TABLE I

SAMPLE DESCRIPTION, GODIN LEISURE-TIME AND FORCE EVALUATION SCORE OF THE PARTICIPANTS AND EFFECTIVENESS OF THE FAMILIARIZATION PERIOD

Participant	Age	Height (cm)	Weight (kg)	Godin Leisure-Time score	FORCE evaluation score (/400pt)	Sujective rating of the familiarization
1	35	168	58	Active	162 - Bronze	Yes
2	36	173	62	Active	348 - Silver	No
3	42	180	63	Active	301 - Bronze	Yes
4	43	177	77	Active	269 - Bronze	No
5	24	172	71	Moderately active	220 - Meets the standard	No
6	29	184	76	Active	343 - Silver	No
7	29	170	70	Active	326 - Bronze	Yes
8	40	168	77	Active	350 - Silver	No
9	25	184	84	Active	377 - Silver	No
10	38	173	81	Active	317 - Bronze	Yes
11	38	172	65	Moderately active	86 - Meets the standard	Yes
12	23	186	69	Active	281 - Bronze	No
13	32	170	61	Active	340 - Silver	Yes

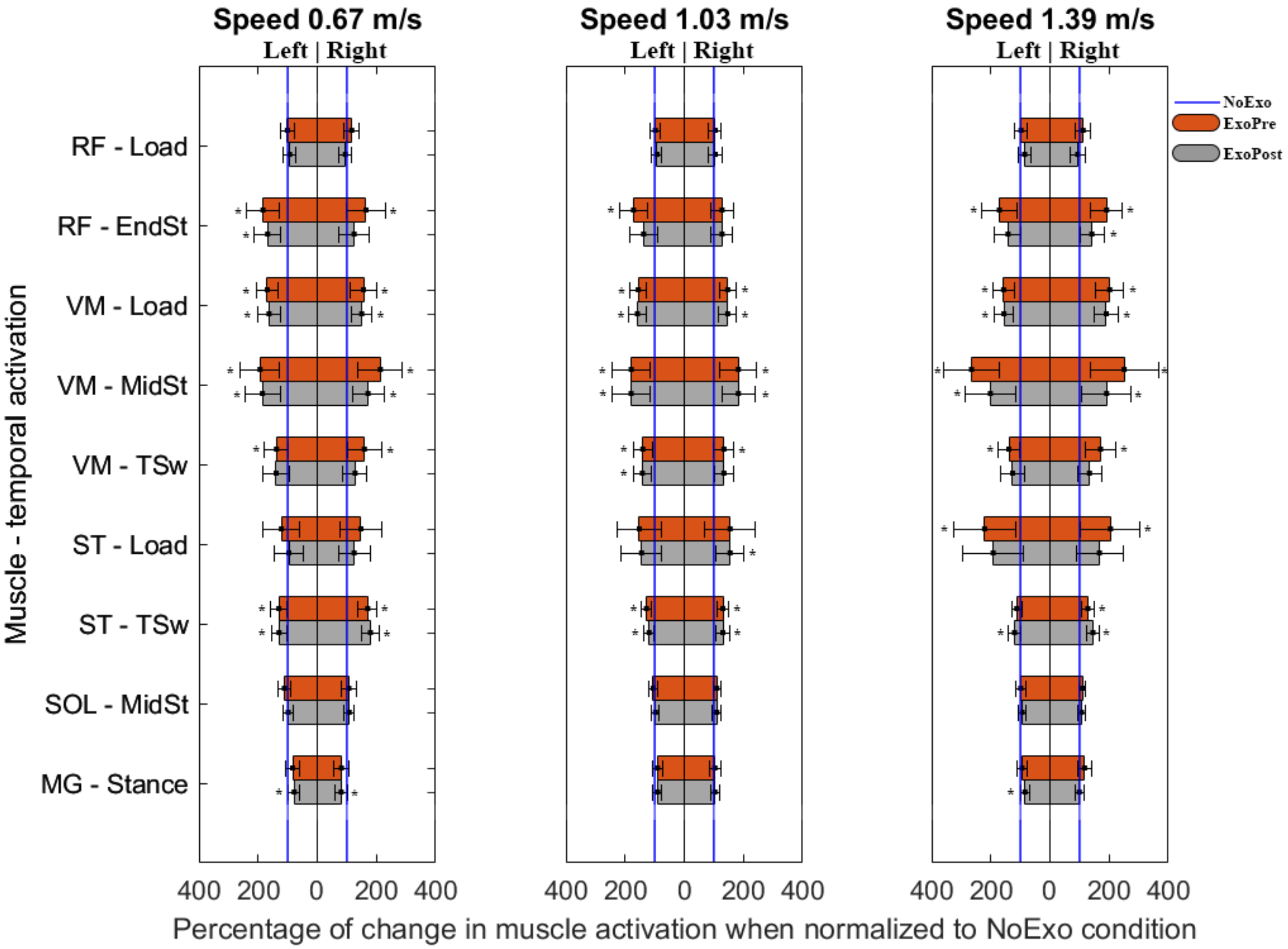

Fig. 5. Muscle activation normalized using the peak activation of the NoExo condition during walking at 0.67 m/s (right), 1.03 m/s (middle) and 1.39 m/s (left). The bar represent the mean activation for each condition and the error bars represent the 95% CI. If the error bars do not touch the NoExo condition (blue line), the difference if statistically significative ($p < 0.05$).

in the current study. As observed by Browning et al., (2007), the MCW increases as mass and distance of load from the participant's center of mass increases [43]. Given the difference in mass of the Gen 3 customizable exoskeleton of the previous study [23] compared to this Gen 4 adjustable exoskeleton (7 kg versus 10 kg respectively), the greater increase in MCW during ExoPre condition may be explained by the larger mass of the Gen 4 device used in the current study. This increase in oxygen consumption may be explained by increased muscle activation of the lower limbs when walking. A recent study evaluating the effect of two load conditions on muscle activations when placed at three locations (i.e., shank (+0.91 kg & +1.81 kg), thigh (+0.91 kg & +1.81 kg) and pelvis (+3.63 kg & +7.26kg)) during walking reported an increase in muscle activity between load conditions for the vastus medialis, gastrocnemius, rectus femoris and biceps femoris, and an increase in muscle activity due to load location for the gastrocnemius, soleus and biceps femoris [44]. We observed similar results in the RF - EndSt, VM (Load, MidSt and TSw) and ST - TSw at 0.67 m/s, 1.03 m/s and 1.39 m/s mph with no significant differences after familiarization except for the right rectus femoris during end stance at 0.67 m/s. Contrary to the previous study, we observed no difference in muscle activity of the soleus and even a decrease in muscle activation of the medial gastrocnemius at 0.67 m/s and 1.39 m/s after familiarization. According to the results of previous studies [43], [44], we may hypothesize that the lower limb section of the exoskeleton, which added around of 2.25 kg to each leg, may have changed the inertia of the leg while walking and in turn affect gait pattern, kinematic and kinetic parameters. These alterations may have led to an increase in muscle activation and a higher MCW during first exposure to the exoskeleton.

After familiarization with a customized exoskeleton, the MCW in three military personnel returned to baseline levels (i.e., an increase of 1.78%) [23]. However, in the current study, when results we're taken as a group, the MCW remained increased by 13.45% after familiarization with an adjustable exoskeleton. A limitation of this study, and a factor potentially influencing motor learning in the current study may be the recruitment. The current study protocol was originally developed to evaluate the influence on the exoskeleton on the MCW and muscle activation in Canadian soldiers. However, given the unforeseen changes to military priorities related to the COVID pandemic at the last minutes, soldiers were no longer available. Therefore, physically fit civilian adults were recruited to evaluate the exoskeleton in place of soldiers. Although the inclusion criteria were targeted to recruit highly fit individuals that may be similar to soldiers (i.e., the Godin Leisure-Time Exercise Questionnaire, the FORCE physical evaluation, and a load carriage familiarization), the familiarization period to the exoskeleton was created specifically for military personnel (i.e., modified based on comments from the previous study [23]. Given that the familiarization period was not customized to the users, it may be hypothesized that familiarization did not meet the users' needs as they could have adapted to the specific task of phase B and C instead of the exoskeleton.

According to Cronbach and Snow., (1977), high ability learners may respond better than low ability learners in a low structured environment (e.g., variable and random practice with more autonomy and independence) [45]. The familiarization period in the current study was designed with variable and random practice based on various tasks that soldiers are accustomed to performing. Therefore, civilians may not have been as familiar with the task demands of the familiarization period. Moreover, task-specific practice that focuses on performance of functional tasks that are meaningful to the individual is an important element of motor learning. [46]. Based on current research, learning is maximal when a specific meaningful task is practiced [47], [48], which can trigger changes in cortical representations [49]. Given that the participants were civilians who were not trained in any military activity, and that the exoskeleton was designed for military use (i.e., to transfer load from the user to the ground in static and dynamic conditions), the familiarization period likely did not contain meaningful tasks for the participants (e.g., the agility and military obstacle course in Phase B and Phase C). Moreover, it has been suggested that task-specific training should focus on improving performance in functional tasks through goal-directed practice [50]. Based on previous findings [23], the familiarization period contained task representatives of soldiers' goals. However, it is likely that the goals were not representative of civilians. Other principles of motor learning (e.g., distribution of practice and focus of attention) may be affected by cognitive, personality differences and individual preferences [51]–[53] that were not considered for the civilians in this study. Future studies should consider how various principles of motor learning may apply to the targeted population.

The variability in the adjustability of the exoskeletons (i.e., comparing the Gen 3 and Gen 4), the ratio between the mass of the exoskeleton versus the payload of the participant and the difference in design should also be considered. Given the Gen 3 exoskeleton was customized according to the anthropometry of each participant (i.e., 3D scan and modeled on them), the fit and adjustment were optimized to each individual. Although the adjustability of the Gen 4 exoskeleton facilitated fitting to a broader population, the precision of the adjustments and fit were less optimal. As stated by Stirling et al., (2020), a good fit is important for effective performance with exoskeletons and increasing the complexity of the equipment requires sophisticated fitting criteria (e.g., 3D anthropometrical information) [54]. Furthermore, improper adjustment may lead to inefficiencies when using a wearable device or equipment [55]. Moreover, adjustable exoskeletons have multiple parts that can be fine-tuned independently, thereby increasing the complexity of the system. This, in turn could increase the time to adapt to the device [56]. We could also hypothesize that improving the joint mobility and range of motion in the Gen 4 exoskeleton could had the consequence of reducing the load transfer capacity. Finally, as a passive load-bearing exoskeleton, the mass of the exoskeleton in this study was transported by the participant. As stated previously, metabolic cost increases linearly with load carried [14], [20], thus, wearing a passive load-bearing exoskeleton would reduce the load carried by the participant and therefore lead to an increase in metabolic cost that is non-linear in relation to the load carried. In our study, a load of 22.75 kg was used to explore the influence of the exoskeleton on MCW and muscle activation. As the exoskeleton is almost half the weight of the load carried, it is likely that the payload of the participant was not enough to "optimally" observe benefits of the exoskeleton. When compared with the previous study, the weight of the exoskeleton was almost one sixth of the payload of the participant and therefore could potentially be beneficial [23].

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This study highlighted important considerations regarding the development, integration, and implementation of familiarization with a passive load-bearing exoskeleton. Integrating a structured familiarization period oriented to specific military operations may not be optimal for all when a non-military participant uses the device. Given the small sample of non-military, these results cannot be generalized to military populations or to a broader population. In terms of design, there may be some benefits to integrating an adjustable exoskeleton on the market as it may be cheaper and more accessible to potential users compared to a customized exoskeleton. However, there may be compromises between performance, efficiency and overall cost related to the adjustability of the exoskeleton. It would be important in future studies to explore the satisfaction and usability of the exoskeleton as well as to consider a hybrid version of the exoskeleton that may reduce the weight while increasing potential user benefits. The effect of different payloads during load carriage and the influence of individualized familiarization periods should also be considered in the future.

V. CONCLUSION

These results suggest that the adjustable passive load-bearing exoskeleton increases muscle activation and MCW during first exposure for all speeds tested. However, the familiarization period did not provide any metabolic or physiological benefits during walking at either low, fast or preferred speed for all participants. The objectives of reducing the physiological burden were not attained when analysed as a group, but a small sample of participants showed potential benefits of the load-bearing passive exoskeleton after familiarization. There might also be some injury prevention mechanisms that we did not evaluate. Future development of passive load-bearing exoskeleton should be focused on evaluating the injury prevention mechanisms and in terms of design, reducing the weight of the device while maintaining most of the adjustments.

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