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Title

Changes in the distribution of muscle activity when using a passive trunk exoskeleton depend on the type of working task: a high-density surface EMG study

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Abstract

Exoskeleton effectiveness in reducing muscle efforts has been usually assessed from surface electromyograms (EMGs) collected locally. It has been demonstrated, however, that muscle activity, redistribute within the low back muscles during static and dynamic contractions, suggesting the need of detecting surface EMGs from a large muscle region to reliably investigate changes in global muscle activation. This study used high density surface EMG to assess the effects of a passive trunk exoskeleton on the distribution of low back muscles' activity during different working tasks. Ten, male volunteers performed a static and a dynamic task with and without the exoskeleton. Multiple EMGs were sampled bilaterally from the lumbar erector spinae muscles while the hip and knee angles were measured unilaterally. Key results revealed for the static task exoskeleton led to a decrease in the average root mean square (RMS) amplitude (~10%) concomitantly with a stable mean frequency and a redistribution of muscle activity (~0.5 cm) in the caudal direction toward the end of the task. For the dynamic task, the exoskeleton reduced the RMS amplitude (~5%) at the beginning of the task and the variability in the muscle activity distribution during the task. Moreover, a reduced range of motion in the lower limb was observed when using the exoskeleton during the dynamic task. Current results support the notion the passive exoskeleton has the potential to alleviate muscular loading at low back level especially for the static task.

Keywords: ergonomics, exoskeleton, surface electromyography

1. Introduction

Work-related musculoskeletal disorders (WMSDs), mainly interesting the neck-shoulder and low back regions, rank among the most serious health problems in the occupational sector (Amell and Kumar, 2001; Roquelaure, 2018). WMSDs have a multifactorial origin (Buckle and Jason Devereux, 2002; Hartvigsen et al., 2018); different factors may account for WMSDs, such as repetitive or sustained activity and incorrect postures during work activities (Elders et al., 2003; Punnett et al., 1991; Wickström and Pentti, 1998). The prevention of WMSDs is therefore of crucial interest in the industry sector.

Different approaches have been proposed to reduce the risk of WMSDs. Examples of preventive measures involve modification and/or reorganization of workstations and equipment, the automation of factories, practice of physical activity, postural and muscle activity re-education using biofeedback (Carayon et al., 1999; Falla et al., 2007; Holtermann et al., 2008; Neumann et al., 2002; Zare et al., 2015). More recently, industrial exoskeletons have been proposed to support workers in sustained or repetitive tasks. Briefly, these body-worn assistive devices are generally classified according to a) the targeted region to be supported (e.g., upper limbs, trunk, lower limbs, or whole-body) and b) the actuation mechanism: active (requiring an external power source) or passive (De Looze et al., 2016). While passive exoskeletons are being adopted by manufacturing companies, active exoskeletons are mainly in a development stage due to their challenging design (e.g., the weight of the device; De Looze et al., 2016; Graham et al., 2009).

Electromyography has been extensively used to assess the effectiveness of passive exoskeletons in muscle effort reduction. The standard bipolar technique is usually applied to estimate the level of muscle activity (Abdoli-Eramaki et al., 2006; Bosch et al., 2016; Graham et al., 2009). However, because of local sampling, bipolar electromyogram (EMG) could be not fully representative of the whole muscle activity (Merletti et al., 2003). For instance, it has been demonstrated the distribution of EMG activity obtained from the lumbar muscles significantly changes during a fatiguing task and cannot be tracked using a standard bipolar detection (Falla et al., 2014; Tucker et al., 2009). This poses some methodological challenges in the assessment of lumbar exoskeleton which likely explain the wide range of percentage attenuation of low back muscles' activity using passive exoskeletons across studies (from 10 to 60%; De Looze et al., 2016; Koopman et al., 2019) and contradictory results between static and dynamic tasks (Baltrusch et al., 2019; Bosch et al., 2016). The detection of muscle activity from a representative muscle region seems therefore essential to assess differences induced by the use of exoskeletons in low back muscles' activity.

This study aimed at investigating the spatial distribution of low back muscles' activity when using a passive trunk exoskeleton during different working conditions. In virtue of the attenuation effect of passive exoskeletons on the level of low back muscles' loading (Abdoli-E et al., 2006; Bosch et al., 2016; Graham et al., 2009) and changes in the EMG distribution over lumbar muscles during simulated working conditions (Falla et al., 2014; Tucker et al., 2009), we expected to observe changes in muscle activity level dependent on the detection site.

2. Material and methods

2.1 Participants and experimental procedures

Ten male volunteers were recruited (mean ± SD; age: 28 ± 2.8 years; body mass: 74.5 ± 7.5 kg; height: 178 ± 0.6 cm) and provided written informed consent before the study. The experimental procedures were conducted following the *Declaration of Helsinki* and approved by the Regional Ethics Committee (Commissione di Vigilanza, Servizio Sanitario Nazionale—Regione Piemonte— ASL 1—Torino, Italy). Subjects were instructed to perform two simulated working activities (one static and one dynamic) with and without a passive trunk exoskeleton (Laevo v2.57, Delft, The Netherlands). The order of the four trials was randomized for each subject and a rest time of 30 minutes was observed between two consecutive trials.

2.2 Working conditions

In the static task, subjects were instructed to maintain a posture with the trunk flexed at 45 degrees with the knees slightly bent and upper arms hanging down vertically (Figure 1A). Participants were provided with visual feedback of the right hip flexion angle on a monitor screen (see. 2.3.2 Joint angles) to keep it within a range of 10% (±5%) of its initial value (Tucker et al., 2009). The trial was stopped by the experimenter when the participant was not able to maintain the required posture (endurance time).

In the dynamic task, subjects were asked to repetitively move, with squat technique, a wooden box (10 kg; Falla et al., 2014; Baltrusch et al., 2019) between two surfaces placed at 50 cm and 100 cm from the floor. The contour of the box was marked on both surfaces to ensure participants would place the box in the same position during the task (Abdoli-E et al., 2006). The repositioning task (one lifting and one lowering) was performed at a cadence of 1task/8s for 10 minutes (right panel in Figure 1A), provided by a metronome. Before starting the task, subjects were familiarized with it for approximately one minute.

2.3 Data acquisition

2.3.1 Surface EMG

Monopolar EMGs were sampled from back muscles bilaterally with two electrode grids positioned serially (16x4 of electrodes, inter-electrode distance: 10 mm; Figure 1B) to cover most of the lumbar erector spinae and multifidus muscles (Falla et al., 2014). Before the application of electrode grids, the skin was cleaned with abrasive paste. A reference electrode was placed over T5. EMGs were recorded with a wearable system for high-density surface EMG (Figure 1B; 10-500 Hz bandwidth, LISIN, Politecnico di Torino, Turin, Italy; Cerone et al., 2019).

2.3.2 Joint angles

To investigate the effects of exoskeleton on the postural strategy, right hip and knee joint angles were collected (Twin-Axis Electrogoniometer SG150, Biometrics Ltd., Newport, United Kingdom). Goniometers were positioned as shown in Figure 1A. A linear encoder (Draw wire sensor, series SX80, WayCon Positionsmesstechnik GmbH, Taufkirchen, Germany) was used to acquire the vertical box movement to discriminate the lifting and lowering phases throughout the repetitive task. All signals were sampled synchronously during the working tasks at 2,048 Hz using a 16-bit A/D converter.

2.4 Electromyographic and kinematic analysis

Monopolar surface EMGs were first visually inspected. Whenever any electrode presented contact problems, the corresponding signal was interpolated by averaging the signals from the adjacent electrodes. Single-differential EMGs (SD EMGs) were calculated along the muscle's longitudinal axis and band-pass filtered (20 – 450 Hz, anti-causal fourth-order Butterworth). Since the endurance time was different for the static task between conditions, the shorter endurance time was considered to define the duration of the contraction for both. The maps of the root mean square (RMS) and mean power spectral frequency (MNF) of SD EMGs were computed over the first (0-10%), middle (40-50%), and last (90-100%) decile of the task duration to study muscle fatigue (Cifrek et al., 2009). For the dynamic task, the lifting and lowering phases were identified respectively as the intervals corresponding to the positive and negative values of the first derivative of the height of the box (Figure 2A). For each movement phase, RMS and MNF maps were calculated for the first, middle, and last minute of the task by averaging the EMG variables across the cycles within the considered minute (Figures 2B and 2C).

The average RMS, the average MNF, and the coordinates of the centroid of the RMS distribution were calculated as global descriptors of each EMG map considering only the channels with RMS higher than 70% of the maximum value in the map (Figure 3; Vieira et al., 2010). The average RMS and MNF were normalized for the highest value across their respective maps, considering both exoskeleton conditions.

Hip and knee joint angles were low-pass filtered (10 Hz, anti-causal 2^{nd}-order Butterworth filter). The average angular position for the static task and the maximum and minimum joint angles for the dynamic task were computed for the three considered periods of the task. The average duration of lifting and lowering phases across cycles was computed to test whether participants keep a constant lifting and lowering pace with the exoskeleton.

2.5 Statistical analysis

Normal distribution of data was verified in both static and dynamic tasks (Kolmogorov-Smirnov, $p > 0.05$ in all cases). A three-way repeated-measures ANOVA was used to evaluate the effect of Time

(3 levels: start, middle, end), Exoskeleton (with and without), and Side (left and right; between factor) on the global descriptors of EMG maps. Furthermore, a three-way repeated-measures ANOVA was applied to compare the maximum and minimum angles between dynamic conditions with Time and Exoskeleton as repeated measures and, Cycle phase, as between factor. A two-way repeated-measures ANOVA was used to compare the average joint angles during the static tasks, with Exoskeleton as between factor. Whenever any significant difference was revealed by ANOVA, paired comparisons were assessed with the Tukey-HSD post hoc test. Finally, a Student *t*-test for paired samples was applied to test for differences in i) the endurance time and ii) the average duration of lifting and lowering phases between with and without the exoskeleton. The level of statistical significance was set at 5%.

3. Results

The visual analysis of the signals commonly revealed good signal quality (Figures 2-4). The average number of interpolated signals was 10 out of 128 channels per subject, considering all tested conditions.

3.1 Static task

Figure 4 shows raw signals and RMS maps for a representative participant. RMS maps showed lower amplitude with than without the exoskeleton during the whole static task, regardless of the trunk side (Figures 4C-D). In both conditions, RMS distribution shifted in caudal direction over time (Figures 4C-D).

ANOVA revealed significant effects of Exoskeleton ($F=10.611$, $p=0.004$) and Time ($F=6.339$, $p=0.004$) on the RMS amplitude. On average, a significant RMS reduction (~10%) was found with exoskeleton ($p<0.005$) and between the beginning and end of the task (~5%; $p=0.001$; Figure 5A). MNF was dependent on the interaction between Time and Exoskeleton ($F=5.044$, $p<0.011$); MNF reduced at the end of the task without the exoskeleton ($p<0.001$; Figure 5B). A significant Time main effect for the y-coordinate of the centroid ($F=4.119$, $p=0.024$) was observed, with muscle activity shifting more distally (~0.5 cm) toward the end of the task in both conditions (Figure 5C; $F>3.730$, $p=0.042$).

For the knee angle, a main effect of Time was identified (F=4.119, p=0.027) with higher values at the end (14.22 ± 13.34 degrees) than at the beginning of the task (9.34 ± 11.62 degrees; p=0.021) while there was a trend to higher hip angle values toward the end of the static task (F=2.881, p=0.069). The endurance time was about two times longer with (10.037 ± 3.40 min) than without exoskeleton (6.107 ± 2.13 min; p<0.01).

3.2 Dynamic task

The RMS distribution differed between exoskeleton conditions. For the representative subject, a stable distribution was observed over time with the exoskeleton while a redistribution arose markedly toward the end of the task without the exoskeleton (Figure 6). Surface EMGs with relatively lower amplitude were detected with than without exoskeleton mainly at the beginning of the task (Figure 6).

For the lifting phase, RMS was dependent on the interaction between Time and Exoskeleton (F=5.011, p<0.012), with lower EMG amplitude (~5%) with than without exoskeleton at the beginning of the task (Figure 7A). For MNF, there was a Time main effect (F=3.286, p=0.048), with lower values toward the end of the task (Figure 7B; p<0.001). For the centroid in the cranial-caudal direction, ANOVA revealed a trend toward an interaction between Time and Exoskeleton (F=2.816, p=0.073). By pooling data, muscle activity tended to shift more distally at the end of the task without than with the exoskeleton (~0.5 cm; Figure 7C).

For the lowering phase, RMS was dependent on the interaction between Time and Exoskeleton (F=4.783, p=0.014). A significant lower RMS (~5%) was found at the beginning of the task with than without the exoskeleton (p<0.05; Figure 8A). For MNF, ANOVA revealed significant effects of Time (F=11.274, p<0.001) and Exoskeleton (F=4.813, p=0.041), showing an increase in MNF from the beginning to the end of the task for both conditions (~5%; p<0.05), but with lower values with than without exoskeleton (Figure 8B).

ANOVA revealed a Time effect on the hip joint for both cycle phases ($F>4.949$, $p<0.012$), with a decrease of maximum (Δ:~8.0 degrees; p=0.018) and minimum (Δ:~3.0 degrees; p=0.020) angles, regardless of the device condition (Figure 9A). A significant main effect of Exoskeleton was revealed for the knee maximum angle (F=8.729, p=0.008), with a lower angle (~6.5 degrees) with than without exoskeleton, regardless of the cycle phase (Figure 9B). For the knee minimum angle, a significant interaction between Time and Exoskeleton was revealed (F=3.675, $p<0.035$), indicating a more flexed knee position with than without the exoskeleton at the beginning of the task (p=0.003).

No differences in the duration of movement phases were observed between conditions without (lifting: 1.328 ± 0.05 s; lowering: 1.463 ± 0.054 s) and with exoskeleton (lifting: 1.341 ± 0.06 s; lowering: 1.446 ± 0.065 s; $p>0.357$ in both cases).

4. Discussion

4.1 Static task

4.1.1 Global EMG amplitude and frequency

The average RMS was about 10% lower with than without the exoskeleton throughout the static task (Figure 5A). These findings are in agreement with previous works on Laevo (Bosch et al., 2016; De Looze et al., 2016; Koopman et al., 2019) and other trunk exoskeletons (Graham et al., 2009). Additionally, we observed a decrease in RMS in both conditions and a decrease in MNF without the exoskeleton over time (Figure 5B). The decrement in EMG MNF and RMS in time could be related to changes in subject posture because of unconscious knee and hip flexion during static bending. It was reported the load sharing between lumbar active and passive tissues in maintaining a flexed trunk posture is influenced by lumbar flexion; less lumbar muscle activation is needed when lumbar flexion increases (Alessa and Ning, 2018; Arjmand and Shirazi-Adl, 2005; McGill, 2002). In any case, the kinematic changes in time should not affect the observed effect of Exoskeleton on muscle activation since they were not different between conditions, suggesting eventual changes in back muscle length over the exertion (and then in the EMG pick up area) should be equal between conditions. The marginal decrement in RMS during both conditions could originate, alternatively, from another factor unrelated to muscle activity, i.e., sweat accumulation. We observed few instances of low-quality

EMGs in the grid possibly because of subjects' sweating. EMG amplitude may be more sensitive to the sweat accumulation underneath the electrodes when compared to MNF (Abdoli-Eramaki et al., 2012). In this case, we could consider the possibility that the decrease of MNF without the exoskeleton can be an indication of higher muscle fatigue (Figure 5; Cifrek et al., 2009). Thus, our findings seem to suggest the passive exoskeleton Laevo decreases muscle intensity and delays muscle fatigue at low back during the static task. The observed exoskeleton reductions in muscle activity (~10%) were however relatively low when compared to previous studies (Bosch et al., 2016; Koopman et al., 2019), thus caution should be taken in its effectiveness on the prevention of musculoskeletal disorders.

4.1.2 The distribution of EMG amplitude

Muscle activity shifted more distally (~0.5 cm) with time in both the exoskeleton conditions (Figure 5C). This corroborates a previous study (Tucker et al., 2009) showing a redistribution of muscle activity during a similar static task with a shift toward the caudal direction. Since lower level of muscle activity (RMS) was detected with than without exoskeleton (Figure 5A), EMG redistribution maybe not necessarily associated with muscle intensity when using the exoskeleton but for how long the lumbar muscles are activated. This is consistent with the notion that the nervous system may rely on the redistribution of muscle activity to maintain motor output when muscles are exposed to sustained activation (Farina et al., 2008; Tucker et al., 2009). Extending the observation of Bosh et al. (2016), current results suggest increases in endurance time (maintenance of the required posture) with the Laevo exoskeleton depends both on the amplitude and the amplitude redistribution of surface EMGs. Moreover, methodologically, these results indicate different changes in EMG could be observed depending on the portion of muscle the EMG is sampled from. It is likely the use of a single pair of electrodes is among the factors contributing to the highly variable reduction of EMG activity with exoskeleton reported in literature (from 10 to 60%; Bosch et al., 2016; De Looze et al., 2016; Koopman et al., 2019). In general, our results seem to show the use of a passive exoskeleton allows the redistribution of muscle activity with a lower degree of muscle activation during the static task.

4.2 Dynamic task

4.2.1 Global EMG amplitude and frequency

Exoskeleton-related differences in muscle activity for the dynamic task were not as clear as for the static task. A RMS reduction (~5%) was observed with the exoskeleton only at the beginning of lifting repetitions (upper panel in Figure 7A), corroborating previous findings on marginal Laevo effect on muscle activity during this task (Baltrush et al., 2019). Such differences in muscle activity however could be additionally influenced by geometrical factors due to kinematic differences between conditions (knee angle, Figure 9B; Farina et al., 2006). Nevertheless, the absence of between-conditions differences in the hip angle (Figure 9A), often associated with the trunk angle during lifting (Bonato et al., 2002; Falla et al., 2014), suggests exoskeleton-related differences in muscle activity are the likely explanation for these results. Moreover, MNF did not differ between conditions, though it changed over time (Figure 7B). The MNF decrease with a concomitant RMS increase observed with the exoskeleton supports the hypothesis of muscle fatigue, which may be due to the focal overload of the same muscle region during the whole task (Figure 7C), as discussed below. Similarly, reduced RMS was observed at the beginning of lowering repetitions with than without the exoskeleton (Figure 8A). From the middle to the end of the task, however, muscle activity seems to increase with the exoskeleton. These results may derive from the coactivation strategy at the trunk level to overcome the resistance of the exoskeleton during trunk flexion in the lowering phase. Baltrusch et al. (2019), for example, observed a significant increase in the activation of abdominal muscles, especially when lowering with the Laevo exoskeleton. On the contrary, without the exoskeleton, the constant average EMG amplitude disregards this hypothesis. Thus, our results suggest participants overall did not show a decrease of low back muscles' activity but, rather, a likely increase in muscle effort with the use of passive exoskeleton during the whole repetitive task. Here, however, we investigated static and dynamic tasks performed in a sagittally symmetric posture. Whether current findings generalize to modern work, where asymmetric postures and trunk rotation are common, require future investigations.

4.2.2 The distribution of EMG amplitude

Muscle activity tended to redistribute toward lower back regions during the lifting task without the exoskeleton whereas no changes were observed with the exoskeleton (Figure 7C). This result corroborates previous work showing caudal EMGs' redistribution following repetitive lifting without any back support (Falla et al., 2014). With the exoskeleton, our findings revealed a constant RMS distribution over time (Figure 7C). No change in the distribution of muscle activity is often related to the overload of a specific muscle region, contributing likely to muscle fatigue (Farina et al., 2008; Falla et al., 2014). Indeed, the RMS increase and concomitant MNF decrease over time (Figure 7), can be indicative of fatigue of initially recruited motor units (Cifrek et al., 2009). Without the use of the exoskeleton, the overload of the same muscle region did not occur probably because muscle activity redistributes across the muscle regions during the task (Figures 6 and 7C). In this case, the influence of fatigue-induced changes in the trend of EMG variables during the repetitive work (e.g., de-recruitment of fatigued motor units) may explain the reduction in both RMS and MNF from the middle of the task (see white circles in Figures 7A-B). Current findings suggest therefore the physiological adaptation in the neuromuscular system to the repetitive effort (i.e., the redistribution of muscle activity) did not occur with the exoskeleton, which might be one of the concerns when using this device.

4.2.3 Kinematics

Another issue regards the movement strategy with the exoskeleton. When considering the knee joint, a lower knee maximum angle was revealed with than without the exoskeleton (Figure 9B). This is in line with Baltrush et al. (2019), who observed a trend towards reduced range of knee motion with the same exoskeleton, probably due to its resistance to movement. Despite a loss of range of knee motion with the exoskeleton, participants were able to keep a consistent lifting and lowering pace in both conditions. Thus, since exoskeleton led to kinematics changes, future investigations should focus on the exoskeleton design to optimize movement strategies.

5. Conflict of interest statement

There were no known conflicts of interest.

6. Acknowledgements

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Figure Captions:

Figure 1: (A) Simulated working tasks investigated: the static forward bending (left panel) and the repetitive lifting and lowering task (right panel). Right hip and knee joint angles were collected from goniometers. For the hip, one of the goniometer arms was placed laterally over the participant's trunk and the other arm was placed over the lateral midline of participant's femur. On the knee, the goniometer was mounted laterally on the leg. (B) Positioning of electrode grids on the low back muscles bilaterally. The lower edge of the 16x4 electrode grids was roughly positioned at L5 level and ~2 cm laterally from the lumbar spinous process mid-point.

Figure 2: Data analysis for the dynamic task. (A) Identification of lifting (dark grey) and lowering (light grey) phases from the height of the box during one cycle of the dynamic task. Knee and hip angle are also showed. (B) Single-differential surface EMGs sampled from the fourth column of the two grids of electrodes positioned on the left side during one cycle of the dynamic task without the exoskeleton. EMG epochs corresponding to the lifting and lowering phases are highlighted in the dark and light grey rectangles respectively. (C) Expanded view of EMGs epochs in (B) during the lifting phase (dark grey rectangle). Note action potentials do not appear with equally high amplitude in the channels, indicating an uneven distribution of muscle activity.

Figure 3: Single-differential (SD) surface EMGs and RMS distribution of low back muscles activity during the repetitive lifting task and without the exoskeleton. Surface EMGs epochs, sampled during the lifting phase by the electrode on the right side at the beginning (A) and the end (B) of the dynamic task. (C) Average RMS map (interpolation by a factor 8) computed for the lifting phase at the beginning (upper panel) and the end (lower panel) of the task. White and black circles respectively indicate the channels with RMS smaller and higher than the 70% of the maximal RMS value in the map.

Figure 4: (A-B) Single-differential (SD) surface EMGs collected from the electrode grids positioned on the right side at the end of the static task without (A) and with the passive device (B). Maps of RMS distribution of low back muscles' activity (interpolation by a factor 8) during the static task without (C)

and with the passive exoskeleton (D). Note the redistribution of muscle activity to the caudal direction toward the end of the task in both conditions.

Figure 5: Mean (±SE) of the electromyographic indices estimated for the start, middle and end of the static holding with trunk flexion, performed without (white circles) and with (black circles) the passive exoskeleton. The endurance time of non-exoskeleton condition was used to define the duration of the contraction for both conditions. The average RMS (A) and average MNF (B) values were normalized to the highest value obtained between the conditions without and with the exoskeleton. * indicates a main effect of Exoskeleton; # indicates a significant interaction between Exoskeleton and Time ($p < 0.05$).

Figure 6: Maps of RMS distribution (interpolation by a factor 8) of low back muscles' activity at the start, middle and end of the dynamic task for the lifting (A) and lowering (B) phases without (top) and with (bottom) the exoskeleton (same subject than Figure 4). Note the redistribution of muscle activity to the caudal direction toward the end of the task for the condition without exoskeleton in both phases of the dynamic task.

Figure 7: Time course of electromyographic indices (mean ± SE) estimated for the lifting phases of dynamic task. White circles correspond to mean values without exoskeleton, while black circles represent mean values with exoskeleton. # indicates significant interaction between Exoskeleton and Time ($p < 0.05$).

Figure 8: Time course of electromyographic indices (mean ± SE) estimated for the lowering phases of dynamic task. White circles correspond to mean values without exoskeleton, while black circles represent mean values with exoskeleton. * indicates a main effect of Exoskeleton; # indicates a significant interaction between Exoskeleton and Time ($p < 0.05$).

Figure 9: Mean (±SE) of the maximum and minimum hip (A) and knee (B) angle for the start, middle and end of the lifting and lowering phases of the dynamic task, without (white circles) and with (black

circles) the passive exoskeleton. * indicates a main effect of Exoskeleton; # indicates a significant interaction between Exoskeleton and Time ($p < 0.05$).