

Neuromuscular Dynamics of Locomotion-to-Climbing Transitions: Electromyographic Foundations for Adaptive Industrial Exoskeletons

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Abstract: Exoskeletons are increasingly used in industrial settings, yet most are designed for structured, repetitive tasks, limiting their adaptability to dynamic movements. In construction, frequent locomotion tasks require continuous lower-limb engagement, with ladder climbing placing significant demands on coordination and flexibility. During this task, the lower limbs perform most of the workload. Identifying key lower-limb muscles involved in climbing is crucial for developing more adaptive exoskeletons. This study examines walking, vertical ladder climbing, and A-shaped ladder climbing to determine which muscles exhibit increased activation during climbing. Walking serves as the normalization reference in electromyographic (EMG) analysis. EMG signals were recorded from eight right-leg muscles—Biceps Femoris, Rectus Femoris, Tibialis Anterior, Gastrocnemius Medialis, Gastrocnemius Lateralis, Semitendinosus, Vastus Medialis, and Vastus Lateralis—using surface electrodes placed according to standard guidelines. Signals were sampled at 1000 Hz, band-pass filtered (20–450 Hz), rectified, and processed with a 100-ms moving average. Peak Root Mean Square (RMS) values were extracted from each stride, averaged across strides, and normalized to walking (set as 100%). Four healthy adults (mean \pm SD: 35 \pm 1.9 years, 185 \pm 30.4 lbs, 173.4 \pm 2.3 cm) performed both climbing tasks in a controlled lab environment. Results showed that during vertical ladder climbing, four upper-leg muscles—Rectus Femoris (537% \pm 272%), Vastus Medialis (413% \pm 138%), Vastus Lateralis (408% \pm 30%), and Semitendinosus (260% \pm 40%)—were significantly more active than during walking ($p < 0.05$). In contrast, lower-leg muscles, such as the Tibialis Anterior and the gastrocnemius group, showed elevated but non-significant activation. For A-shaped ladder climbing, significant increases were observed in Rectus Femoris (373% \pm 128%), Vastus Medialis (434% \pm 136%), and Vastus Lateralis (355% \pm 61%); Semitendinosus activation was elevated during A-shaped climbing but not statistically significant. Both ladder types intensively engage the quadriceps; however, vertical climbing appears to place additional demands on the hamstrings, particularly the Semitendinosus. These findings help identify target muscles for future exoskeleton support during walking-to-climbing transitions.

Keywords: Electromyography (EMG), Lower-limb muscle activation, Exoskeleton, Ladder climbing, Construction

1. Introduction

Exoskeletons are increasingly adopted to address work-related musculoskeletal disorders (WMSDs) in physically demanding industries. Active exoskeletons—those powered by motors and actuators (Chen et al., 2020)—have demonstrated the ability to reduce muscle effort by up to 80%, particularly in repetitive or load-bearing tasks (De Looze et al., 2016). A recent market analysis identified that 66% of exoskeleton models are designed for industrial applications, while only 14% are intended for the construction sector, and even those are broadly applicable rather than specifically tailored to construction's unique physical demands (Al-Khiami et al., 2024).

However, these devices often lack adaptability for dynamic and transitional tasks commonly observed in construction, such as locomotion from walking to climbing. Ladder climbing, in particular, is a frequent yet biomechanically demanding activity on construction sites and industrial plants, used to transition between levels or access rooftops, tanks, and elevated platforms. This task demands precise coordination, with the lower limbs performing the majority of the climbing effort to maintain stability and balance (Armstrong et al., 2009). Despite its prevalence, ladder climbing remains underexplored in the exoskeleton literature, and only a few studies have addressed it in a limited scope. For example, (Wang et al., 2023) investigated muscle synergies across different climbing phases and found they were not highly correlated, suggesting humans adapt their muscle activation to maintain stability. However, little is known about how lower-limb muscle activation patterns differ from walking.

Muscle amplitude amplification (MYO) has been proposed as a mid-level control strategy in EMG-based exoskeleton systems to adjust actuator support proportionally to muscle activation levels, enabling more responsive and adaptive assistance (Baud et al., 2021). Understanding muscle demands during climbing is, therefore, essential for designing adaptive exoskeleton control strategies. According to (Ko et al., 2020) stair climbing is a mechanically demanding task that requires greater joint range of motion and muscle activity than level walking. Similarly, Bartlett et al. (2014) assessed gluteal muscle activation—specifically the superior and inferior gluteus maximus and gluteus medius—during walking, running, sprinting, and vertical ladder climbing using EMG to compare relative muscle activity across these locomotion tasks. However, limited evidence is available on which specific lower-limb muscles are most engaged during ladder climbing and how their activation differs from walking.

In construction contexts, workers frequently use two main types of ladders: vertical ladders and A-frame (A-shaped) ladders. Vertical ladders are commonly installed in fixed locations for elevation transitions, while A-shaped ladders are portable and often used during finishing, inspection, or assembly work. Determining which muscles are more active in these climbing conditions, relative to walking, is critical before implementing task-specific support through wearable robotics. Rather than focusing on comparing the ladders themselves, the present study aims to identify key lower-limb muscles that show significantly higher activation during climbing, using walking as a baseline

This investigation provides foundational insight into lower-limb muscle engagement during ladder climbing by identifying which muscles exhibit significantly higher activation compared to walking. While this study does not propose or evaluate exoskeleton control strategies, the findings help prioritize muscles that may benefit most from powered assistance. These insights can inform future research aiming to develop adaptive support systems for climbing tasks and enable smoother transitions between walking and climbing within exoskeleton applications.

2. Materials and Methods

The methodology of this study is organized into three main sections: sensor attachment, experiment procedure, and data analysis.

2.1 Sensor Attachment

Surface electromyography (EMG) signals were recorded from eight right-leg muscles using the BTS FREEEMG 1000 system (BTS Bioengineering), a wireless system offering real-time, high-resolution signal acquisition. The muscles monitored were: Vastus Medialis (VM), Vastus Lateralis (VL), Rectus Femoris (RF), Biceps Femoris Caput Longus (BF), Semitendinosus(S), Tibialis Anterior (TA), Gastrocnemius Medialis (GM), and Gastrocnemius Lateralis (GL). Before electrode placement, the skin was cleaned with alcohol to reduce impedance. Electrodes were aligned with the direction of muscle fibers and placed on the muscle belly following SENIAM guidelines to optimize signal quality (SENIAM, n.d.). EMG signals were sampled at 1000 Hz. Disposable Kendall™ 200 series Ag/AgCl electrodes with a foam substrate and hydrogel adhesive were used to ensure consistent skin contact and secure placement throughout the trials. Figure 1 illustrates the experimental setup, including the BTS FREEEMG 1000 system, the two types of ladders used in the climbing tasks (A-shaped and vertical), and an example of EMG sensor placement on the right leg. The anterior (left) and posterior (right) views of the right leg, as shown in Figure 2, illustrate the placement of EMG sensors. Only the right leg was instrumented in this study.



Figure 1. (a) BTS FREEEMG 1000 wireless electromyography system; (b) A-shaped ladder used for climbing trials; (c) Vertical ladder setup in the lab environment; (d) EMG sensor placement on the right leg.

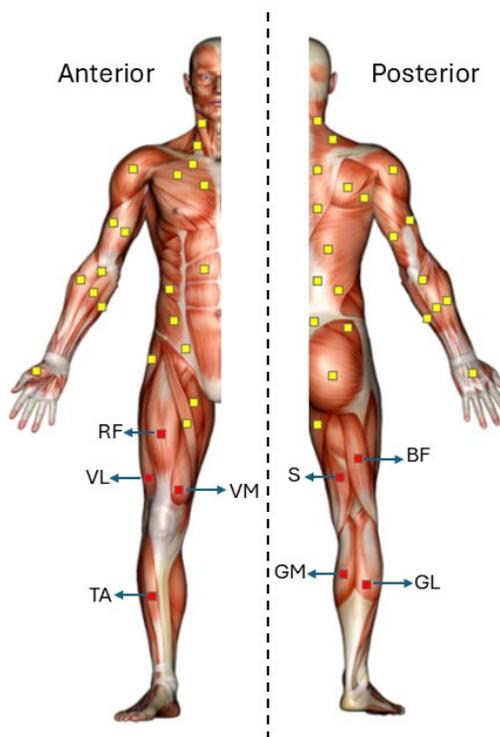


Figure 2. Locations where EMG sensors were placed on the right leg muscles. TA: Tibialis Anterior, VM: Vastus Medialis, VL: Vastus Lateralis, RF: Rectus Femoris, BF: Biceps Femoris Caput Longus, S: Semitendinosus, GM: Gastrocnemius Medialis, GL: Gastrocnemius Lateralis

2.2 Experiment Procedure

Four healthy male graduate students (mean age: 35 ± 1.9 years; height: 173.4 ± 2.3 cm; weight: 185 ± 30.4 lbs), all with no history of lower-limb musculoskeletal injuries in the past six months, participated in the study. All participants provided informed consent prior to their involvement, and the experimental protocol was approved by the university's Institutional

Review Board (IRB). Each participant performed the tasks at a self-selected, comfortable pace to reflect natural movement. The experiment involved two types of ladders: a vertical ladder with twelve rungs and an A-shaped ladder commonly used in construction with seven rungs. Participants climbed up to the eighth rung on the vertical ladder and up to the fifth rung on the A-shaped ladder to maintain the three-point contact rule and minimize instability that could occur at higher elevations. To align EMG data with locomotion phases, synchronized video recordings were used to manually identify stride events. Walking strides were segmented based on consecutive right heel contacts with the ground. For the vertical ladder, three strides were selected based on right foot contact with the first, third, and fifth rungs. For the A-shaped ladder, two strides were extracted from the segment where the right foot contacted the first, third, and fifth rungs. For each ladder condition, three walking strides were also extracted from the approach phase immediately before the climb. All trials were performed under similar indoor conditions, and rest periods were provided between tasks to minimize fatigue.

2.3 Data Analysis

The raw EMG signals were band-pass filtered using a 4th-order Butterworth filter with cutoff frequencies of 20–450 Hz to remove motion artifacts and high-frequency noise. The filtered signals were then full-wave rectified and smoothed using a 100-ms moving average to compute the EMG activation envelope. From each locomotion condition, walking and vertical ladder climbing, three strides were identified per participant. Due to the shorter usable height of the A-shaped ladder, only two strides were available for that condition. For each stride, the peak RMS value was extracted for each of the eight lower-limb muscles.

$$Peak_{s,j}^{Condition} = \max(RMS_{s,j}^{Condition}) \quad (1)$$

These stride-specific peaks were then averaged across the available strides:

$$\overline{Peak}_{i,j}^{Condition} = \frac{1}{S} \sum_{s=1}^S Peak_{s,j}^{Condition} \quad (2)$$

To evaluate changes in muscle activation during climbing, the average peak values were normalized to the walking baseline:

$$Normalized\ EMG_{i,j}^{Condition} = \frac{\overline{Peak}_{i,j}^{Condition}}{Peak_{i,j}^{Walking}} \quad (3)$$

where s is the stride index, i is the participant index, j denotes the muscle (1–8), and Condition refers to walking, vertical climbing, or A-shaped climbing. $RMS_{s,j}^{Condition}$ is the smoothed EMG signal, $Peak_{s,j}^{Condition}$ is the peak RMS per stride, and \overline{Peak} is the average peak across strides. A value greater than 1.0 indicates increased muscle activation during climbing relative to walking. Group-level means and standard deviations were calculated across participants for each muscle and condition. The Shapiro–Wilk test was used to assess the normality of each muscle’s distribution. Depending on the outcome, either a one-sample t-test or a Wilcoxon signed-rank test was applied to determine whether normalized climbing activation significantly differed from the walking baseline (1.0). Results were visualized using bar charts showing group means \pm standard deviations, with statistically significant differences ($p < 0.05$) indicated by asterisks.

3. Results and Discussion

This section presents the EMG-based findings comparing muscle activation during walking, vertical ladder climbing (Climb V), and A-shaped ladder climbing (Climb A). The goal was to identify which lower-limb muscles exhibit increased activation during climbing tasks and whether those changes differ by ladder type. Figure 3 presents normalized EMG amplitudes (mean \pm SD) for eight right-leg muscles during walking and climbing tasks. Walking values were set to 1.0 for each participant and muscle, and climbing values were normalized accordingly. “Climb V” and “Climb A” represent vertical and A-shaped ladder climbing, respectively. Asterisks (*) indicate statistically significant differences from walking ($p < 0.05$), determined by one-sample t-tests or Wilcoxon signed-rank tests. The Y-axis is limited to 9.0 for visual clarity. In general, upper-leg muscles (quadriceps and hamstrings) exhibited greater activation than lower-leg muscles across both climbing conditions. Among the quadriceps group, Vastus medialis and Vastus lateralis showed the highest increases. Vastus medialis

reached 413% ± 138% (Climb V) and 434% ± 136% (Climb A), both statistically significant (p = 0.0294 and 0.0237). Vastus lateralis also showed significant increases: 408% ± 30% (Climb V) and 355% ± 61% (Climb A) (p < 0.05).

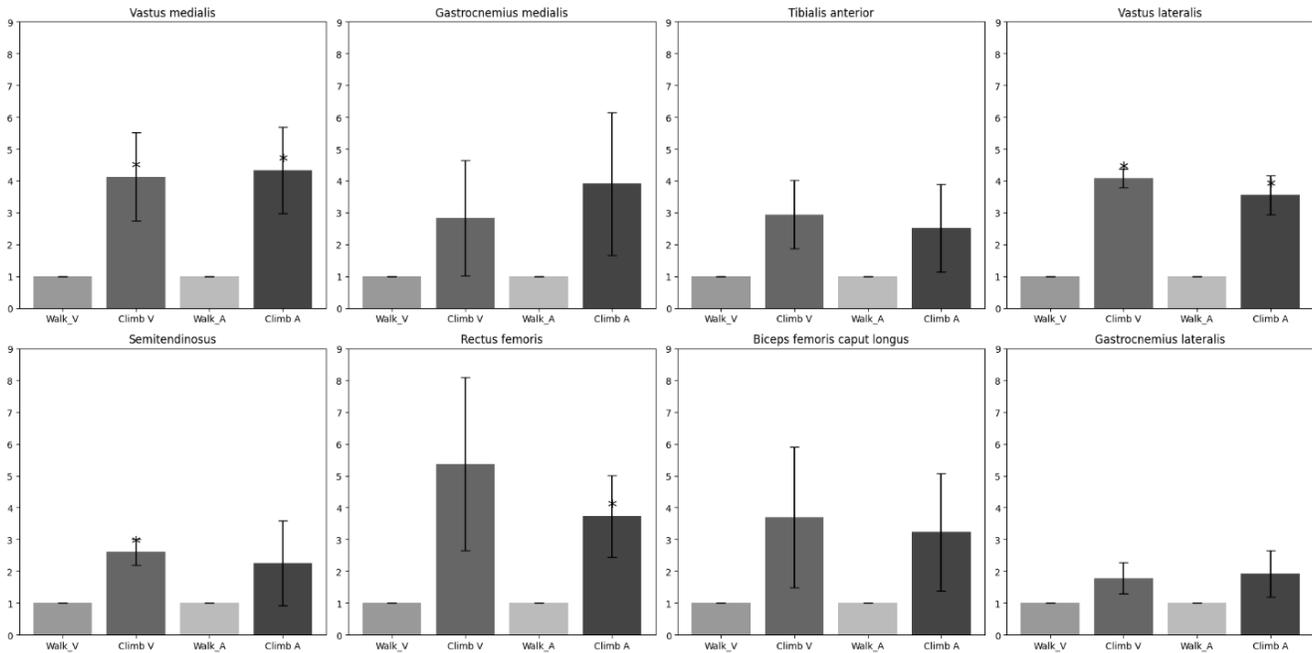


Figure 3. Normalized EMG (mean ± SD) for eight right-leg muscles during walking and climbing. Asterisks (*) indicate p < 0.05 vs. walking.

Table 1 summarizes the activation levels (as a percentage of walking) for muscles that demonstrated statistically significant increases during at least one climbing condition. This table helps highlight the most engaged muscles relevant to climbing assistance.

Table 1. EMG activity during ladder climbing expressed as a percentage of walking (mean ± SD). Only muscles with significant increases are shown. *p < 0.05 vs. walking

Muscle (Right leg)	Climb V (% ± SD)	Climb V p-value (vs. 1.0)	Climb A (% ± SD)	Climb A p-value (vs. 1.0)
Vastus medialis	413% ± 138%	0.0294 *	434% ± 136%	0.0237 *
Vastus lateralis	408% ± 30%	0.0047 *	355% ± 61%	0.0276 *
Semitendinosus	260% ± 40%	0.0063 *	-	-
Rectus femoris	-	-	373% ± 128%	0.0346 *

The Semitendinosus, which contributes to hip extension and knee flexion, was significantly more active during vertical climbing (260% ± 40%, p = 0.0063), but not in the A-shaped condition. Its limited role in angled climbing may reflect the reduced need for hip extension in that posture. Rectus femoris, which supports both hip flexion and knee extension, exhibited a significant increase during A-shaped climbing (373% ± 128%, p = 0.0346), but not in vertical climbing. This suggests that task-specific joint angles and body posture influence how this biarticular muscle is recruited. The Tibialis anterior, involved in dorsiflexion, showed moderately elevated activation during Climb V (294% ± 107%) but did not reach statistical significance (p = 0.0517). Both Gastrocnemius medialis and lateralis, muscles typically engaged in plantarflexion and knee assistance, showed relatively low activation and no statistical significance in either climbing task. In summary, the quadriceps muscles, especially Vastus medialis and Vastus lateralis, play a dominant role during both climbing conditions. The selective activation of Semitendinosus and Rectus femoris depending on ladder type highlights how movement mechanics shape muscle demand. These insights can inform adaptive exoskeleton design strategies aimed at supporting ladder-based locomotion in construction environments.

4. Conclusions

This study identified lower-limb muscles with significantly increased activation during vertical and A-shaped ladder climbing compared to walking. The quadriceps muscles, particularly Vastus medialis and Vastus lateralis, were consistently and substantially engaged in both ladder types. Semitendinosus activation increased significantly only during vertical climbing, while Rectus femoris was more active in A-shaped climbing. This finding may suggest potential task-specific muscle recruitment, though a larger sample is needed to confirm this trend. In contrast, lower-leg muscles such as the Tibialis anterior and gastrocnemius group showed elevated but non-significant activation levels. While their roles appeared less dominant, Tibialis anterior and gastrocnemius lateralis exhibited relatively low variability, suggesting that the lack of significance may be due to limited statistical power rather than inconsistent activation. Increasing the sample size in future studies may clarify whether these muscles play a more consistent role in climbing tasks.

Overall, this study demonstrates a practical EMG-based method for identifying muscle-specific demands during construction-relevant locomotion that involves ladder climbing. These insights would be valuable for the prioritization of target muscles in phase-based industrial exoskeleton control strategies development. Although limited by a small sample size (N = 4) and controlled laboratory conditions, the findings provide a plausible foundation. Future work should expand the participant pool, including a real-world testing environment, and integrate joint-level analysis to better inform the design of adaptive lower-limb exoskeletons.

5. References

- Al-Khiami, M. I., Lindhard, S. M., & Wandahl, S. (2024). Charting the Exoskeleton Industry: A Comprehensive Insight into Dynamics and Trends. *IOP Conference Series: Earth and Environmental Science*, 1389(1), 012014. <https://doi.org/10.1088/1755-1315/1389/1/012014>
- Armstrong, T. J., Young, J., Woolley, C., Ashton-Miller, J., & Kim, H. (2009). Biomechanical Aspects of Fixed Ladder Climbing: Style, Ladder Tilt and Carrying. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 53(14), 935–939. <https://doi.org/10.1177/154193120905301417>
- Bartlett, J. L., Sumner, B., Ellis, R. G., & Kram, R. (2014). Activity and functions of the human gluteal muscles in walking, running, sprinting, and climbing. *American Journal of Physical Anthropology*, 153(1), 124–131. <https://doi.org/10.1002/ajpa.22419>
- Baud, R., Manzoori, A. R., Ijspeert, A., & Bouri, M. (2021). Review of control strategies for lower-limb exoskeletons to assist gait. *Journal of NeuroEngineering and Rehabilitation*, 18(1), 119. <https://doi.org/10.1186/s12984-021-00906-3>
- Chen, B., Zi, B., Qin, L., & Pan, Q. (2020). State-of-the-art research in robotic hip exoskeletons: A general review. *Journal of Orthopaedic Translation*, 20, 4–13. <https://doi.org/10.1016/j.jot.2019.09.006>
- De Looze, M. P., Bosch, T., Krause, F., Stadler, K. S., & O'Sullivan, L. W. (2016). Exoskeletons for industrial application and their potential effects on physical work load. *Ergonomics*, 59(5), 671–681. <https://doi.org/10.1080/00140139.2015.1081988>
- Ko, S., Kwak, K., Kim, H., & Kim, D. (2020). Effect of Mechanical Stimulation Applied to the Lower-Limb Musculature on Stability and Function of Stair Climbing. *Applied Sciences*, 10(3), 799. <https://doi.org/10.3390/app10030799>
- Surface electromyography: Recommended sensor locations*. (n.d.). Retrieved June 12, 2025, from http://www.seniam.org/sensor_location.htm
- Wang, L., Pang, M., Xiang, K., Luo, J., Tang, B., & Lu, B. (2023). Evaluation of Muscle Activation Reaction on Vertical Climbing. *2023 9th International Conference on Electrical Engineering, Control and Robotics (EECR)*, 42–45. <https://doi.org/10.1109/EECR56827.2023.10150130>