

Ergonomic Analysis of Vertical Ladder Climbing Activity for Active Knee-based Exoskeleton Control Design

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Abstract: Exoskeleton technology is increasingly recognized for its significant potential in mitigating musculoskeletal disorders and enhancing productivity in industrial settings, particularly within manufacturing and construction sectors. Active exoskeletons, which employ motor-driven assistance, have emerged as promising ergonomic interventions, offering substantial improvements in worker biomechanics. Despite these promising developments, exoskeleton solutions available today are primarily task-specific, designed explicitly for activities such as overhead lifting, squatting, or prolonged standing. Given the inherently dynamic and varied nature of construction activities, however, this limited adaptability poses a considerable challenge to effectively utilize exoskeletons across different construction tasks. One particularly dynamic task encountered regularly in construction settings is vertical ladder climbing. Workers frequently climb ladders to access elevated locations such as scaffold platforms, scissor lifts, industrial tanks, or rooftops, posing substantial ergonomic challenges and notable risks for musculoskeletal injuries and falls. Understanding the biomechanics involved in ladder climbing is thus crucial for informing effective exoskeleton design, especially in developing adaptive motor-assistance strategies that respond to varied climbing patterns. This study addresses these ergonomic concerns by conducting a biomechanical analysis of vertical ladder climbing using wearable inertial measurement units (IMUs). The objective of this study is to analyze joint kinematics during ladder climbing in order to support the development of adaptive control strategies for active exoskeletons. Laboratory-controlled experiments involved five healthy adult participants (average age: 35.4 years; weight: 163 lbs; height: 5.6 feet) who performed ladder climbing tasks on an eight-step, 10-foot-high vertical ladder at a comfortable, self-selected pace. Joint angles at the knee and ankle joints (pitch, i.e., flexion-extension) were continuously recorded using six IMUs placed strategically on participants' lower limbs. Two primary findings emerged from the analysis. First, participants demonstrated varied climbing patterns, with some individuals alternating their legs, potentially as a compensatory mechanism for fatigue management or to maintain stability. Second, significant biomechanical differences in knee joint angles were observed, with the right knee angles remaining relatively consistent ($\sim 37^\circ$) across ascent and descent phases, whereas the left knee angles displayed variability (mean ascent: 40.8° ; mean descent: 52.7°), indicating asymmetric loading between legs. Ankle joint angles demonstrated stability, consistently averaging between 25.5° and 27.4° , highlighting their critical role in maintaining overall balance during ladder climbing.

Keywords: Active Lower Limb Exoskeleton, IMU, Ladder Climbing, Construction Activities, Wearable Sensors

1. Introduction

Lower-limb exoskeletons (LLEs) are gaining considerable attention for their potential to mitigate work-related musculoskeletal disorders (WMSDs) and enhance worker productivity and safety, particularly in physically demanding industries such as construction. Research has demonstrated that exoskeleton usage significantly reduces the prevalence of WMSDs, with prevention rates ranging from approximately 15% to 85% for the hip, 25% to 75% for the knee, 30% to 70% for the lower leg and ankle, and 20% to 80% for the upper leg (Okpala et al., 2022). Given these promising outcomes, integrating LLEs into industries characterized by frequent lower-limb activities, such as ladder climbing, squatting, prolonged standing, or walking, is highly beneficial. Construction sites are particularly dynamic work environments involving diverse physical tasks such as wrenching, bricklaying, hammering, drilling, and ladder climbing. Among these tasks, ladder climbing is notably critical due to its regular occurrence and high risk of falls and musculoskeletal disorders, including knee osteoarthritis, knee bursitis, meniscal injuries, and stress fractures (Okunribido & Lewis, 2010). From a biomechanical perspective, ladder climbing creates specific movement constraints, as the worker's hands and feet form fixed contact points with the ladder, necessitating detailed biomechanical analysis to better understand these interactions (Yuan & Chen, 2014).

While both active and passive exoskeletons have been evaluated for supporting ladder climbing activities, specific optimization remains necessary, especially for tasks involving complex movement dynamics such as ladder climbing (Govaerts et al., 2024). Designing effective exoskeleton control strategies for such activities requires a comprehensive understanding of the biomechanical patterns involved (Simonetti et al., 2018). Wearable inertial measurement units (IMUs) have proven highly effective for capturing precise biomechanical data due to their affordability, minimal invasiveness, and compact size (Bangaru et al., 2020). IMUs are widely used for posture monitoring and dynamic movement analysis (Wenk & Frese, 2015). For instance, they have been successfully employed in ladder climbing scenarios to collect accurate motion data, enabling estimation of musculoskeletal stresses and potential injury risks (Petropoulos et al., 2017). Seo et al. utilized IMUs for ladder climbing to collect motion data, which was then analyzed using a force prediction model and the 3DSSPP software to estimate musculoskeletal stresses and identify potential injury risks under real working conditions (Seo et al., 2014). Another study utilized a method for estimating knee joint flexion/extension angles using inertial sensors. The method uses Kalman filters and anatomical constraints, avoiding reliance on the Earth's magnetic field. Two IMUs placed on adjacent body segments provided segment acceleration and angular velocity data. Validated during walking and running, the method showed average measurement errors ranging from 0.7° to 3.4°, demonstrating its effectiveness for dynamic knee angle estimation (Cooper et al., 2009). Despite substantial research on IMU applications, specific studies focusing on joint angle analysis during ladder climbing remain limited. Addressing this gap, this study particularly investigates knee and ankle joint dynamics during vertical ladder climbing, recognizing their essential roles in this activity (Chen et al., 2023). Despite these advancements, a specific gap remains in the literature regarding detailed joint kinematic analysis particularly of the knee and ankle, during vertical ladder climbing. Most existing studies have either focused on general climbing mechanics or applied IMUs without targeting their use for angle-based control strategy development in exoskeleton design. Addressing this gap, this study particularly investigates knee and ankle joint dynamics during vertical ladder climbing to inform and enhance power-control strategies for active lower-limb exoskeletons.

2. Materials and Methods

Five healthy adult participants (four males, one female), aged 28 to 42 years (mean age: 35.4 ± 5.1 years), participated in this study. All participants were free of musculoskeletal disorders and had not experienced lower-limb injuries within the previous six months. Prior to data collection, each participant performed a brief standardized warm-up to minimize the risk of injury and promote consistent movement patterns.

The experimental trials were conducted in a controlled laboratory environment using an industrial-grade vertical aluminum ladder with eight steps and a total height of 10 feet. Participants were instructed to climb the ladder at a self-selected, comfortable pace, pause for 2–3 seconds at the four-step for stabilization, and then descend at the same pace. A brief resting interval was observed between the ascent and descent to segmentate the motion data. A total of six wearable inertial measurement units (IMUs) were used to capture lower-limb kinematics. The IMUs (3-Space Sensors, Yost Labs, USA) are Attitude and Heading Reference Systems (AHRS) that integrate tri-axial accelerometers, gyroscopes, and magnetometers. The locations of the IMUs attached to the participants' lower-limb are illustrated in Figure 1.

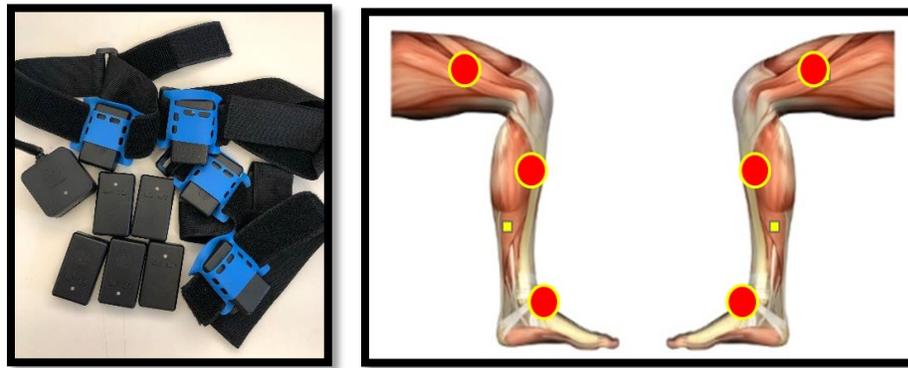


Figure 1: The IMU sensors and their placement on the thigh, shank, and ankle

The IMUs recorded 3D orientation data in quaternion format, which were converted to Euler angles for further analysis (O-lamnithipong et al., 2019). Quaternions are four-dimensional constructs (QuatW, QuatX, QuatY, QuatZ) that represent 3D rotational orientation. However, for interpretation and joint angle computation, these quaternions were converted to Euler angles, specifically extracting the Y-axis rotation (pitch), which corresponds to the flexion-extension movement plane. The conversion from quaternions to Euler Y (pitch) was performed using the following transformation:

$$\text{Euler Y (pitch)} = \arcsin(2(\text{QuatW} \times \text{QuatY} - \text{QuatZ} \times \text{QuatX})) \quad (1)$$

This expression isolates the sagittal plane motion—critical in tasks such as climbing, where forward and backward limb rotations dominate. By focusing on pitch, we reduce the complexity of 3D motion to a single, relevant degree of freedom that reflects functional joint movement. To determine joint angles, the relative orientation between adjacent segments was computed. Specifically:

$$\text{Knee Angle} = \text{Euler Y}_{\text{thigh}} - \text{Euler Y}_{\text{shank}} \quad (2)$$

$$\text{Ankle Angle} = \text{Euler Y}_{\text{Ankle}} - \text{Euler Y}_{\text{shank}} \quad (3)$$

These relative angles represent the flexion-extension relationship between anatomical segments, capturing how one bone segment rotates with respect to another. Figure 2 illustrates the spatial movement concepts for the knee and ankle joints.

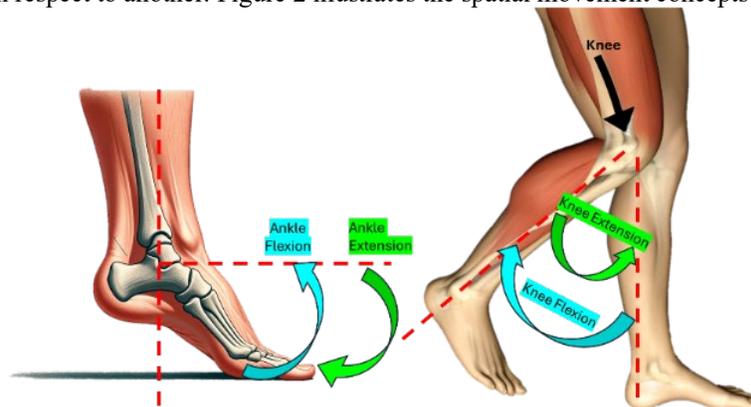


Figure 2: Ankle and Knee Joint's Spatial Movement

Finally, joint angles for each participant were aggregated and analyzed using Python codes running in Google Colab, with custom scripts developed for quaternion-to-Euler angle conversion, signal smoothing, and biomechanical computation. Time-series plots were generated to visualize flexion and extension patterns during ladder ascent and descent. For each joint, five key metrics were computed: mean angle, standard deviation (SD), maximum flexion, full extension, and range of motion (ROM). The mean angle provided a baseline for typical joint positions, while the SD captured inter-individual variability. Maximum flexion and full extension represented the extremes of joint movement, and ROM quantified the total excursion of the joint.

3. Results and Discussion

This study tested the knee and ankle angles of the pitch (flexion-extension) movement captured by 6 Inertial Measurement Units (IMU) sensors. Each participant completed one ascent and one descent phase, with a brief pause in between. Four flexion-extension cycles were observed per phase, matching the number of ladder steps.

The data analysis revealed an interesting behavior among some participants: alternating their legs during the ascent and descent of the ladder. Figure 3 illustrates the difference in stepping strategy observed between the two participants. The top plot illustrates a participant who ascended and descended without switching lead legs, consistently initiating each step with the same limb. This produced sequential peaks in one knee while the other remained relatively static during the swing phase. In contrast, the bottom plot shows a participant alternating legs throughout both ascent and descent, evident by alternating peaks between the left and right knee angle profiles. These differences in movement strategy highlight the individual variability in how ladder climbing is performed. Some users may adopt consistent leg dominance, while others engage both limbs more symmetrically. Such variation is likely influenced by comfort, balance preferences, fatigue resistance, or habitual motor patterns.

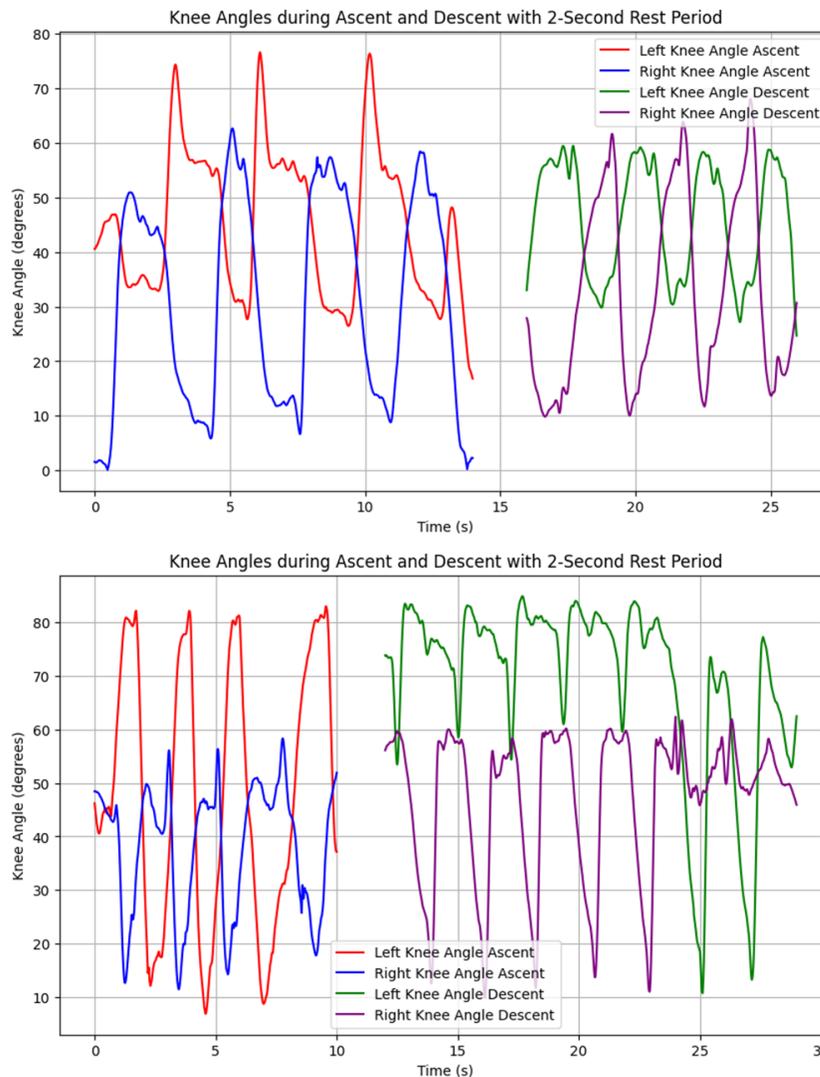


Figure 3. Comparison of knee joint angles during ascent and descent for two participants. The top panel illustrates a participant using a sequential stepping pattern with the same lead leg, while the bottom panel shows a participant alternating legs across steps. Each waveform represents flexion-extension cycles of the left and right knees during four-step climbs in both directions.

These observations carry important implications for exoskeleton design. Exoskeletons must be able to adapt to the variability in human movement patterns, particularly in dynamic tasks like ladder climbing. The power control strategy of an active knee-based exoskeleton should be capable of recognizing and responding to these alternating patterns to provide consistent support.

This study also analyzed the aggregated joint angle data from all five participants, focusing on the right knee and bilateral ankle movements during ladder ascent and descent (Table 1). For reference, the neutral joint position was defined as 0° for full knee extension and for the ankle when the foot is perpendicular to the shank.

Table 1: Combined Knee and Ankle Joint Angles Statistics During Ladder Climbing

	Phase	Joint	Mean (°)	St. D (°)	Max Flexion (°)	Full Extension=0 (°)	ROM (°)
Aggregate Data	Ascent	Right Knee	37.4	20.0	74.0	0.1	73.9
		Left Knee	40.8	20.6	83.0	2.1	80.9
		Right Ankle	27.4	19.2	78.1	7.5	78.1
		Left Ankle	25.5	13.8	62.3	0.0	62.3
	Descent	Right Knee	37.5	20.8	74.1	0.1	74.0
		Left Knee	52.7	20.3	85.0	0.0	85.0
		Right Ankle	26.5	16	69.3	0	69.3
		Left Ankle	27.0	15	77.6	0.0	77.6

During ascent, the mean right knee angle was 37.4°, with a standard deviation (SD) of 20.0°, and a maximum flexion of 74.0°. The corresponding values during descent were nearly identical (mean: 37.5°, SD: 20.8°, max flexion: 74.1°), indicating consistent movement patterns across phases. The minimum extension reached approximately 0°, suggesting that participants consistently extended their knees fully during both ascent and descent. The left knee exhibited greater angular displacement, particularly during descent. The mean left knee angle increased from 40.8° (ascent) to 52.7° (descent), while maximum flexion rose from 83.0° to 85.0°, and the joint consistently reached full extension. These results suggest an asymmetry in lower-limb contribution, with the left knee showing increased activity during descent, potentially due to individual leg dominance or the need for additional support when lowering the body. Ankle joint angles were relatively stable across all participants and phases. Mean ankle angles ranged from 25.5° to 27.4°, with moderate variability (SD: 13.8° to 19.2°), and consistent full extension values. The consistency in ankle movement reflects their stabilizing role during climbing, supporting the findings highlighted in earlier joint trajectory plots.

4. Conclusion

This study investigated the ergonomic characteristics of vertical ladder climbing to inform the design of active knee-based exoskeletons for construction workers. This research focused on knee and ankle joint angles, which play a central role in maintaining stability and enabling controlled motion during climbing. Using six Inertial Measurement Units (IMUs), the flexion-extension (pitch) angles of these joints were recorded in five healthy adult participants as they climbed an 8-step, 10-foot vertical ladder. The data revealed consistent ankle joint behavior and variability in knee joint angles, particularly between the left and right sides and across ascent and descent phases. Importantly, while some participants exhibited a sequential leg movement pattern, others alternated lead legs during the task. This irregularity deviates from typical gait patterns and highlights the importance of designing adaptive exoskeletons capable of supporting diverse and dynamic movement strategies (Ailisto et al., 2005; Murray, 1967). Critically reviewing our findings in light of existing literature, this study reinforces the value of IMUs for capturing joint kinematics in occupational tasks. Prior research has demonstrated their accuracy in estimating knee flexion angles (Cooper et al., 2009) and assessing climbing dynamics (Seo et al., 2014). Our contribution lies in applying these tools specifically to vertical ladder climbing, an activity that remains relatively underrepresented in exoskeleton research, thereby offering new insights into joint variability and postural adaptation during this task.

The contributions of this study are twofold: (1) from a practical standpoint, it offers valuable data to guide the development of active exoskeletons for climbing tasks in construction; and (2) from a scientific perspective, it extends the application of IMU-based motion tracking to a highly dynamic and ergonomically challenging activity. This study presents insights into the biomechanics of vertical ladder climbing using wearable inertial measurement units (IMUs); however, several limitations must be acknowledged. First, the sample size was limited to five healthy adults (four males, one female),

which may restrict the generalizability of the findings. Aggregating data from both male and female participants in a single analysis may overlook potential sex-based biomechanical differences that could influence joint angles or movement strategies. Future studies should include a larger and more demographically diverse participant pool. Second, the ladder climbing task was limited to a vertical ladder with only four steps analyzed, which may not fully replicate the fatigue, variability, or kinematic complexity involved in longer or repetitive climbs. As such, results may differ under extended task duration or in more realistic occupational settings. Future research should incorporate longer climbs or repeated trials to capture the effects of fatigue and real-time adaptation. Third, only vertical ladder climbing was investigated, whereas construction work often involves climbing various structures, such as A-frame ladders or stairs. These structures may elicit different movement patterns, stability challenges, and muscle engagements. Expanding the analysis to include diverse climbing geometries could improve the external validity and adaptability of exoskeleton design recommendations. Additionally, the current study focused solely on flexion-extension (pitch) angles and did not evaluate other degrees of freedom (e.g., roll and yaw), which could provide a more comprehensive understanding of joint movement in three dimensions. Incorporating multi-axis analysis in future work may reveal additional insights into joint stability, control requirements, and risk of injury. Finally, while IMUs are effective for kinematic tracking, future research could integrate other sensing modalities, such as electromyography (EMG) or force plates, to better understand muscle activation patterns and load distribution, thereby enhancing the physiological relevance of biomechanical interpretations.

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