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✦ Original Article

Characterization Of Heel-Hook, Drop-Knee, And High-Step Movements In Climbers' Knees

Christian Ramírez MSc[1]*

1. Pontificia Universidad Javeriana, Bogotá

***Correspondence:** ccramirez20@gmail.com

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Abstract

Background: There is limited quantitative information regarding the forces, moments, and joint angles involved in specific climbing movements that have been frequently associated with knee injuries, such as the drop-knee, high-step, and heel-hook. Understanding the mechanical demands of these techniques may help characterize how the knee is loaded during climbing.

Purpose: To characterize the knee joint angles, external forces, and moments generated during the execution of the drop-knee, high-step, and heel-hook movements in male climbers.

Methods: Motion capture was performed over one week to record the execution of three climbing movements on an indoor wall by eight right-handed male climbers. An instrumented climbing hold equipped with strain gauges was used to estimate external forces in the y- and z-axes. Knee joint angles were obtained from motion capture data, and external moments were estimated using a simplified rigid body diagram. Participant demographics and methodological details were standardized to support reproducibility.

Results: Significant differences were observed between movements in external moments, knee angles, and forces. The drop-knee and high-step generated higher external moments than the heel-hook (P = 0.002 and P = 0.00002). Knee flexion angles differed significantly between the drop-knee and heel-hook (P = 0.003). Forces in the z-axis were higher for the drop-knee and high-step compared to the heel-hook (P = 0.002 and P = 0.0002), and the force expressed as a percentage of body weight was also greater in these two movements (P = 0.0009 and P = 6E−6). Forces recorded for the heel-hook in the y-axis were limited due to measurement constraints.

Conclusion: The three movements elicited distinct mechanical demands on the knee. On average, the drop-knee and high-step generated external forces equivalent to approximately 20% of body weight, while the heel-hook showed lower values under the experimental setup used. These findings provide initial quantitative insights into knee loading during common climbing movements. Further research—including measurement of forces in all three axes, consideration of wall inclination, and inclusion of climbers with varying experience levels—is needed to clarify how specific movement characteristics may contribute to injury risk.

Introduction

Rock climbing is a high-intensity sport in which individuals ascend natural or artificial rock walls using only their limbs. Although climbing has been practiced for decades, its popularity has grown rapidly in recent years, particularly following its inclusion in the Tokyo 2020 Olympic Games. This expansion is reflected globally, with more than 25 million people estimated to participate regularly and a sustained increase in the number of indoor climbing facilities (2,13,14,10). The growth of climbing gyms in some regions (for example, the United States) has been notable in recent years (9). As participation grows, so does the relevance of understanding the physical demands and potential injury risks associated with the sport.

Bouldering—short, high-intensity climbing performed without ropes on low walls with padded flooring—has become one of the most popular disciplines. The dynamic and explosive nature of bouldering movements has been frequently associated with a higher occurrence of injuries compared to other styles of climbing (3,4,6,14). Lower-extremity injuries have been reported to represent between 12.7% and 27.6% of all climbing injuries, and approximately 10% involve the knee (8,15,3). While knee injuries remain relatively uncommon overall, their impact on climbers can be substantial, and the absolute number of cases is expected to increase alongside the sport's continued growth.

Several studies have described that specific climbing movements are more frequently reported in association with knee discomfort or injury. Among these, the drop-knee, high-step, and heel-hook techniques—along with falls—are consistently mentioned as movements during which climbers often experience knee-related issues (13). These reports, however, do not establish causation, and the underlying biomechanical mechanisms through which these movements may load the knee joint remain poorly understood. Existing literature provides limited quantitative data on the forces, joint angles, and external moments involved in these specific techniques. As a result, the mechanical demands placed on the knee during climbing are not yet well characterized, particularly when compared to common daily or athletic activities (7,16,12).

A clearer understanding of the joint-loading patterns involved in these movements is essential to support future research into injury mechanisms and potential preventive strategies. Therefore, the objective of this study was to characterize the knee joint angles, external forces, and external moments generated during the drop-knee, high-step, and heel-hook movements in climbers. We hypothesized that these movements would generate substantial mechanical demands on the knee and that the loading patterns would differ between techniques, reflecting their distinct movement characteristics rather than assumed injury risk. (13)

Methods

Study design

The research took place in the Ergonomics Laboratory at Pontificia Universidad Javeriana in the city of Bogotá, Colombia. An indoor climbing wall was constructed, and four Vicon T-Series cameras were strategically positioned within the capture area (Figure 1).

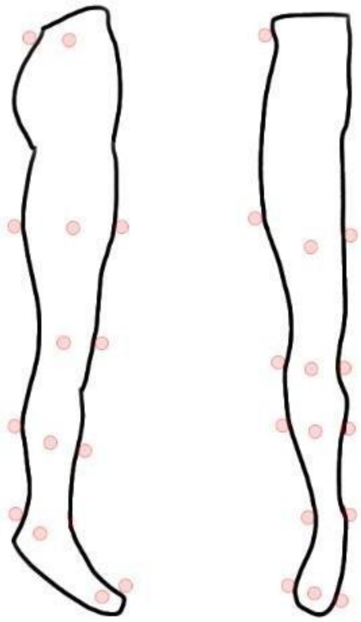
Figure 1. Experimental setup where the climbing wall and the cameras used can be seen.

To evaluate the effect of each climbing movement executed on a specific route, climbing holds were placed on the wall. For each movement, a set of holds was selected (Figure 2).

Figure 2. Climbing wall with colored holds representing the designated holds for each movement. The yellow holds indicate the heel-hook, the red holds indicate the drop-knee, and the green holds indicate the high-step.

Markers were placed along the right leg of the participants as shown in Figure 3. A total of 19 reflective markers were utilized. This distribution was chosen to ensure that each segment of the leg had at least two markers to track the entire execution of each technique. The leg was divided into three segments: the thigh (upper leg), calf (lower leg), and foot. The length between the knee and the ankle was measured from the lower part of the patella to the lateral malleolus as reference, and the length between the ankle and the foot was measured from the lateral malleolus to the tip of the big toe (hallux).

Figure 3. Marker positions used during motion capture on the right leg.

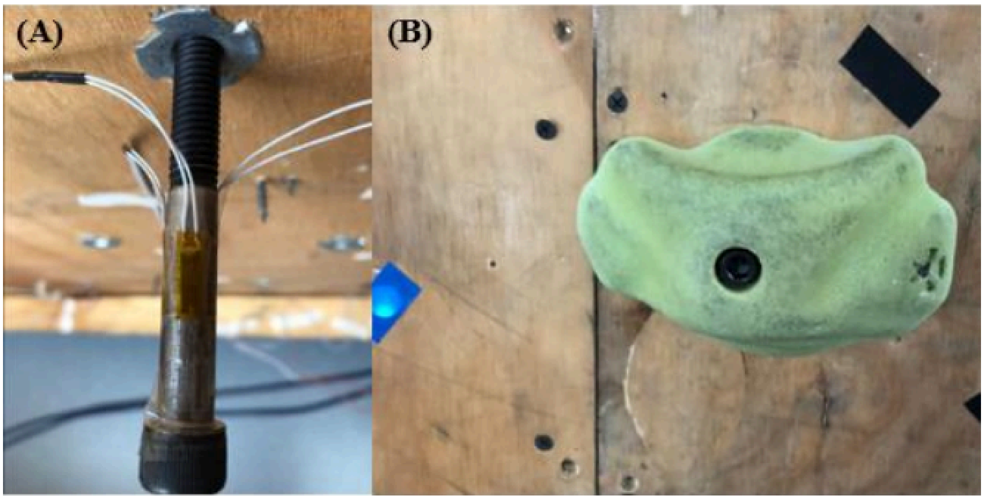


Two additional markers were placed on the climbing wall to obtain the horizontal vector generated between them (M_1 and M_2). Through motion capture analysis, three angles were identified: the knee joint angle of maximum flexion, the angle between the lower leg and the horizontal (φ), and the angle between the foot and the horizontal (ɑ). These angles were calculated using vectors generated between two markers for each segment via the dot product (Equation 1), where θ (RT) is the thigh-to-horizontal angle, and M (MM) is the knee moment.

$$\theta = cos^{-1}\frac{\overrightarrow{RT}.\overrightarrow{M_1M_2}}{|RT||M_1M_2|} \qquad (1)$$

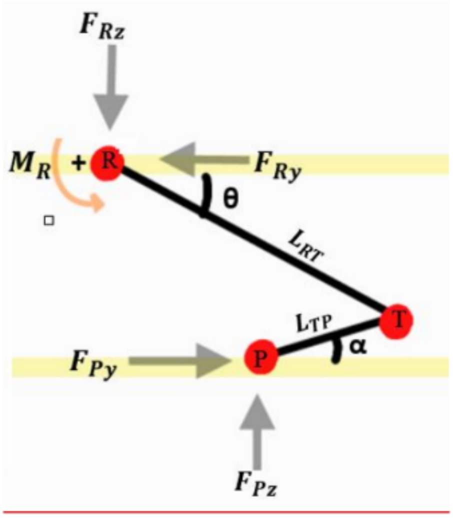
An instrumented climbing hold was built using three strain gauges from the company Omega. These strain gauges were evenly placed every 120° on the screw and then embedded inside a climbing hold. The connection was concealed behind the wall (Figure 4). Subsequently, the climbing hold was calibrated for the z-axis and y-axis. The strain generated on the screw was measured using Ingemoduler, a tool specifically designed for processing strain gauge information and converting it into strain. Force was determined by analyzing the strain generated on the screw and applying the linear regression equations derived from the calibration process. For heel-hook, y-axis forces were lower (2.83% ± 1.61% BW) due to some readings near instrument noise, yielding n=4.

Figure 4. (A) Instrumented screw with three strain gauges (Omega) at every 120°. (B) Instrumented climbing hold as seen from the climber's perspective.



The climbers were instructed to warm up, and once the markers were in place, they were asked to perform each movement once maximally, following a 3-minute rest period to minimize fatigue. A rigid body diagram was created for each movement, allowing analysis of forces on the foot and angles measured through motion capture. By utilizing this diagram, the force and moment exerted on the knee during execution were determined (Figure 5).

Figure 5. Rigid body diagram for the drop-knee movement showing forces, angles, and moment.



Statistical analysis was conducted using Microsoft Excel and Microcal Origin 6.0. The data obtained were assessed for normality using the Shapiro-Wilk test. For normally distributed data, paired t-tests were employed to determine statistical differences between movements (significance threshold: $P < 0.05$). No multiple-comparison corrections were applied. In cases where data did not follow a normal distribution, Kruskal-Wallis analysis was utilized.

Results

Table 1 presents a summary of the participants' demographics and morphological measurements. All participants were male climbers with a right dominant leg. The data exhibiting the greatest variability was climbing time, with an average of 7.24 ± 6.35 years. The group included both novice and nationally elite climbers.

Table 1. Participants demographics and morphological measurements

Variable	Mean ± SD
Participants (n)	8
Age (years)	27.38 ± 5.04
Mass (kg)	71.00 ± 10.03
Weight (N)	695.80 ± 98.28
Height (cm)	176.38 ± 5.83
Years climbing	7.24 ± 6.35
Knee–ankle length (m)	0.40 ± 0.01
Ankle–toe length (m)	0.20 ± 0.01

Table 2. Summary of Forces, Knee Angles, and External Moments for Each Movement.

2A. Drop-Knee

Variable	Mean ± SD	p-value
Z-axis force (N)	141.16 ± 62.39	0.92
Z-axis force (% body weight)	20.24 ± 7.29	0.43
Y-axis force (N)	132.21 ± 87.41	0.64
Y-axis force (% body weight)	18.51 ± 11.37	0.54
Knee angle (°)	43.98 ± 8.72	0.99
External moment (Nm)	68.83 ± 46.07	0.99
External moment per unit mass (Nm/kg)	0.98 ± 0.67	0.89

2B. High-Step

Variable	Mean ± SD	p-value
Z-axis force (N)	162.57 ± 55.73	0.95
Z-axis force (% body weight)	22.91 ± 5.90	0.69
Y-axis force (N)	121.19 ± 59.66	0.46
Y-axis force (% body weight)	16.96 ± 7.36	0.58
Knee angle (°)	58.28 ± 19.26	0.57
External moment (Nm)	−37.45 ± 21.72	0.85
External moment per unit mass (Nm/kg)	−0.53 ± 0.38	0.61

2C.Heel-Hook

Variable	Mean ± SD	p-value
Z-axis force (N)	36.95 ± 24.69	0.23
Z-axis force (% body weight)	5.77 ± 4.45	0.22
Y-axis force (N)	19.36 ± 9.03	0.62
Y-axis force (% body weight)	2.83 ± 1.61	0.93
Knee angle (°)	17.87 ± 10.12	0.65
External moment (Nm)	1.83 ± 8.81	0.93
External moment per unit mass (Nm/kg)	0.03 ± 0.15	0.49

For strain gauge calibrations, an adjacent averaging filter was applied to remove noise. After obtaining data for each mass, two linear regressions (three points each) were performed for the z-axis and y-axis:

$$z\ axis$$

$$y = (6.58E - 6 \pm 5.86E - 7)x - (7.37E - 6 \pm 8.02E - 6)$$

$$R = 0.96257$$

$$y\ axis$$

$$y = (1.56E - 6 \pm 2.10E - 7)x + (6.41E - 6 \pm 2.88E - 6)$$

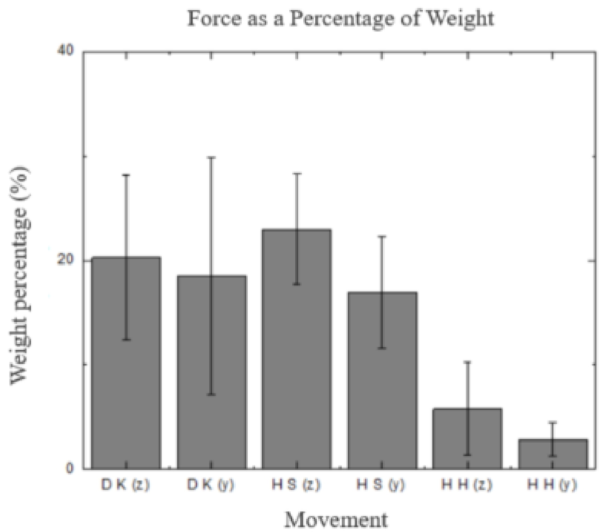
$$R = 0.92017$$

These R^2 values indicate significant correlation, validating the equations for force calculations.

When calculating heel-hook forces, some participants recorded data not differing significantly from instrument noise; thus, only four y-axis measurements were obtained from eight participants.

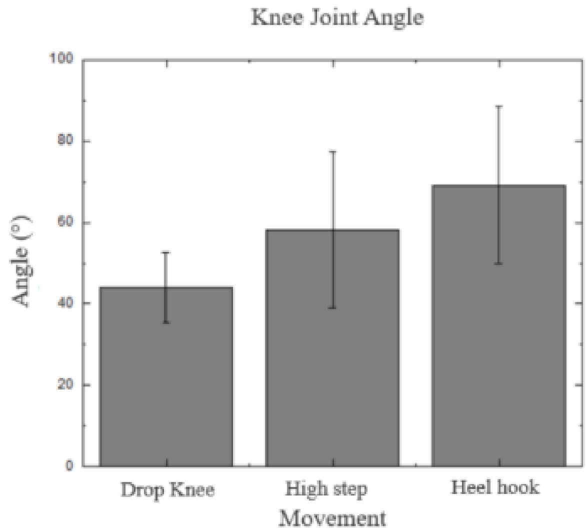
Average forces as percentages of body weight were 20.54% ± 7.92% (drop-knee) and 22.99% ± 5.26% (high-step) in the z-axis, and 5.77% ± 4.45% (heel-hook) in the z-axis. Y-axis forces: 18.51% ± 11.37% (drop-knee), 16.96% ± 5.36% (high-step), 2.83% ± 1.61% (heel-hook) (Figure 6).

Figure 6. Force as percentage (%) of body weight in each movement for y- and z-axes. Data as mean ± SD.



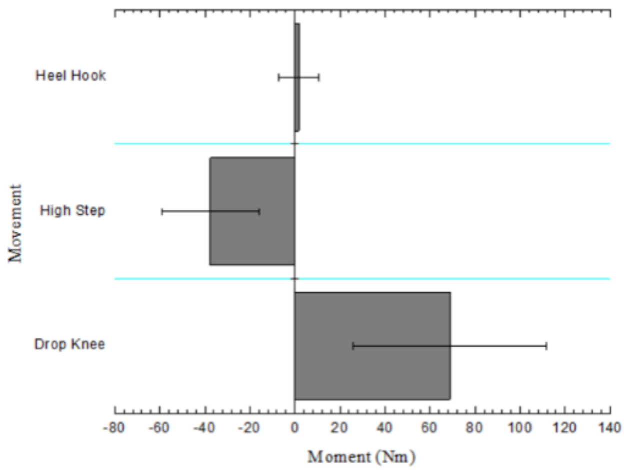
Knee joint angles (thigh-hip to calf-knee vectors at maximal force onset) were 43.93° ± 8.72° (drop-knee), 58.28° ± 19.26° (high-step), 69.17° ± 16.12° (heel-hook) (Figure 7).

Figure 7. Maximum knee flexion angle (°). Data as mean ± SD.



Horizontal angles used wall markers (M_1-M_2 vector) with thigh (θ) and foot (α) segments, yielding knee moments: 68.83 ± 46.07 Nm (drop-knee), -37.45 ± 21.71 Nm (high-step), 1.83 ± 8.81 Nm (heel-hook). Positive values indicate counterclockwise moment (Figure 8).

Figure 8. Knee moment (Nm). Data as mean ± SD.



Significant differences ($P < 0.05$):

- Moment: drop-knee vs. heel-hook ($P = 0.002$); high-step vs. heel-hook ($P = 0.00002$).
- Knee angles: drop-knee vs. heel-hook ($P = 0.003$).
- Z-axis forces: drop-knee vs. heel-hook ($P = 0.002$); high-step vs. heel-hook ($P = 0.0002$).
- Z-axis % body weight: drop-knee vs. heel-hook ($P = 0.0009$); high-step vs. heel-hook ($P = 0.000006$).
- Y-axis heel-hook tests were not performed due to negligible data.

Discussion

This study characterizes forces, moments, and angles in drop-knee, high-step, and heel-hook movements in climbers' knees. These movements are associated with knee injuries, underscoring the need to understand their mechanics for prevention strategies. Indoor research with artificial walls is relevant, as most injuries occur in indoor bouldering.

Literature reports walking moments per unit mass of 0.458-1.265 Nm/kg. Study values ranged from -1.61 to 0.34 Nm/kg (mostly negative, counterclockwise). Magnitudes were similar to walking. These represent external moments from measured forces and segment lengths; comparisons to walking/internal torques (e.g., extensor: 100.9 Nm at 20°; flexor: 76.1 Nm at 20°) require caution due to methodological differences.

The heel-hook was expected to show highest loads due to injury associations, but yielded lowest values (Table 2). X-axis forces (into/out of wall) were not measured, potentially underestimating heel-hook loads, as heel traction may involve x-axis components. Results are specific to the 90° wall; steeper angles likely increase demands.

Lutter et al. associated drop-knee/high-step injuries with dynamic force peaks during hold transitions, not evident here. Z-axis knee forces ranged 0.01-0.34 × BW, lower than walking (2.1 ± 0.2 × BW).

Drop-knee showed greatest flexion (43.93° ± 8.72°), with angles 35.08°-100.51° generally in safer ranges (<90°). Heel-hooks exceeded 100° in some cases.

Study limitations

This study has several limitations that should be considered when interpreting the findings. First, the sample size was relatively small and included only right-handed male climbers between 22 and 35 years of age, which limits the generalizability of the results to other populations, such as women, left-handed climbers, or older and younger athletes. In addition, participants varied in experience level, ranging from novice to nationally elite climbers, and the study was not designed or powered to analyze differences between experience groups.

A second limitation is related to the experimental setup. Only one indoor climbing wall with a fixed height and a vertical (90°) inclination was used, which restricted the evaluation of movements performed on steeper or more complex walls. The relatively low height of the wall may have constrained movement execution for taller individuals, and using a single instrumented hold reduced the analysis to one specific contact configuration and phase of each movement, rather than capturing the full variability of climbing routes.

A third limitation concerns the measurement of forces. The instrument held measured forces only in the y- and z-axes, while forces in the x-axis (towards and away from the wall) were not recorded. This is particularly relevant for the heel-hook, where substantial traction along the x-axis is likely and could lead to an underestimation of the total load acting on the knee joint. Moreover, for the heel-hook, some y-axis measurements were close to the noise level of the device, resulting in a reduced number of valid trials for that variable and limiting the robustness of the corresponding analyses.

Finally, the study focused on external forces, joint angles, and external moments at the knee, without directly assessing internal joint loads, ligament stresses, or muscle activation patterns. As a result, it is not possible to establish causal relationships between the measured variables and specific injury mechanisms. The present work should therefore be viewed as an initial characterization of the mechanical demands of drop-knee, high-step, and heel-hook movements, and future studies are needed to incorporate three-dimensional force measurements, detailed neuromuscular models, and stratification by experience level to provide a more comprehensive understanding of how these movements are associated with knee injuries in climbers.

Conclusions

This study provides initial quantitative data on the external forces, knee joint angles, and external moments generated during the execution of the drop-knee, high-step, and heel-hook movements. On average, the drop-knee and high-step produced external forces equivalent to approximately 20% of body weight at peak loading under the conditions tested. The drop-knee demonstrated the greatest knee flexion among the three movements, while the heel-hook exhibited distinct loading characteristics within the limits of the measurement setup.

Interpretation of the heel-hook must be made with caution. In this study, forces were measured only in the y- and z-axes, and the wall geometry did not reflect common scenarios in which climbers typically perform heel-hooks. Because the X-axis components (traction, rotation, and abduction) are relevant for this movement but were not captured, the present findings do not fully characterize heel-hook loading.

Further research is necessary to better understand the loading patterns and potential biomechanical factors associated with knee discomfort or injury during climbing. Important next steps include incorporating measurement of forces in all three axes, using motion-capture models that can quantify full joint rotations, and integrating analyses of muscle activation. Expanding the sample to include climbers of different experience levels, genders, and limb dominance would also improve generalizability.

Although the forces and angles measured in this study were not extreme compared to values reported in other biomechanical contexts, a more complete understanding of rotational loading and multi-planar joint behavior is needed to determine how knee structures are stressed during climbing techniques. Strengthening muscles involved in knee flexion and extension (such as the quadriceps and hamstrings) remains broadly recommended in the literature, but should be interpreted as general guidance rather than a direct implication of our findings. Proper technique and controlled execution of movements may also help climbers better distribute load across the limbs involved.

Overall, this study serves as an exploratory step toward characterizing knee joint loading in common climbing techniques. Continued efforts to develop more comprehensive biomechanical models will help clarify how forces are distributed across the knee and will support future research into technique optimization and injury prevention strategies.

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No funding was received for this research.

Competing interests

The author declares no potential conflict of interests.

Data availability statement

Data is available upon request to the corresponding author.

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