biomechanics

Communication

Biomechanical Analysis of Elite Ice-Climbing Performance

Missy A. Thompson *, Dylan Blair, Morgan Shippen and Sean Toma

Health & Human Performance Department, Fort Lewis College, Durango, CO 81301, USA
* Correspondence: mathompson@fortlewis.edu; Tel.: +1-970-247-7580

Abstract: Competitive ice climbing involves ascending ice and natural rock/manmade features using specialized equipment. Despite its growing popularity, there is limited knowledge regarding the relationship between ice climbers' biomechanics and performance. The purpose of this study was to analyze spatiotemporal variables and upper-extremity joint kinematics during an elite lead ice-climbing competition. A total of 24 (16 male, 8 female) competitors participated. Video data was recorded during the ice climbing competition, and biomechanical analysis software was used to measure kinematic variables (shoulder and elbow angles) and spatiotemporal (time climbing/resting and number of moves/rests) throughout a section of the competition route. Independent *t*-tests examined differences between the top and bottom 50% of competitors, and correlations assessed the strength of the relationship between the measured variables and competition rank. We found a strong correlation between elbow and shoulder angles at weight bearing on the ice tool, indicating that ice climbers rely on more extended arm positions, which may decrease muscle fatigue, maintain optimal muscle fiber lengths, and keep the trunk close to the wall with lower contact forces. Additionally, we found that higher-performing ice climbers moved faster with fewer moves, which is likely due to their ability to identify specific holds as affordances to guide their movement.

Keywords: ice climb; performance; biomechanics

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1. Introduction

Competitive ice climbing involves ascending ice and natural rock/manmade features using specialized ice-climbing equipment. The sport is rooted in alpinism but has evolved into a distinct sport with unique equipment designed for its specific demands. The sport of ice climbing currently consists of two-sub disciplines: speed and lead. The speed discipline focuses on how quickly a climber can ascend a set route, while the lead discipline emphasizes the climber's ability to navigate a challenging route with technical skill and strategic planning. Lead-difficulty events, governed by the Union Internationale des Associations d'Alpinisme (UIAA), are typically conducted on artificial ice structures to ensure consistency and difficulty across competition routes. Climbers are belayed from below and ascend in a lead format, which involves clipping quickdraws in sequence. Competitors generally have only one attempt per round, except for the qualification round, where a second attempt is permitted if the first quickdraw is not clipped. Each climber is given a set time to complete the route, starting when they begin their ascent and ending upon a fall or completion of the route. Results are primarily determined by the height the climber reached, with time also considered if the route is finished within the allotted time or if competitors reach the same height. The sport of ice climbing has seen considerable growth in recent years, and the inclusion of ice climbing in the Winter Olympics has been a significant goal for the sport. The UIAA has been actively promoting ice climbing's entry into the Olympic program since its demonstration at the 2014 Sochi Winter Olympics.

Ice climbing is highly related to other subunits of climbing, which include traditional climbing, sport climbing, and bouldering, that have seen considerably more research than the sport of ice climbing. Saul et al. [1] reviewed the scientific literature related to climbing performance, finding that successful climbers typically exhibit anthropometric traits of low body fat, small calf circumferences, and substantial forearm volume. Further, forearm, finger, and grip strength and endurance, as well as oxidative capacity and reoxygenation, were factors associated with climbing performance. Additionally, Orth et al. [2] conducted a systematic literature review of perceptual and movement data during climbing tasks graded for difficulty, finding that elite climbers excel at detecting climbing opportunities when visually inspecting a route from the ground and when physically moving through a route.

There are several biomechanical aspects of ice-climbing techniques that have been found to contribute to an ice climber's competitive skill level. Seifert et al. [3] found that expert ice climbers demonstrated higher variability in limb movement than novice climbers. Additionally, Seifert et al. [4] found that expert ice climbers demonstrated diverse limb coordination patterns and fewer exploratory movements, indicating effective use of icefall features to enhance performance, whereas beginners exhibited repetitive actions and lower motor variability, reflecting a lack of perceptual attunement to the climbing environment. Two particularly important aspects of ice climbing are the strike motion of the ice axe and arm position (shoulder and elbow angles) during the swing and upon weight bearing on the ice tool. The strike motion of an ice climber's ice axe is a technical move that secures the climber to the ice and allows them to ascend the wall. Robert et al. [5] defined the two phases of the strike motion: (1) the cocking phase, where the ice axe moves to its furthest posterior position, and (2) the striking phase, where the ice axe is swung anteriorly, coming into contact with the ice. Robert et al. [5] concluded that elite ice climbers demonstrated significantly different axe swings than novice climbers.

Despite the growing popularity of ice climbing, there is a lack of knowledge regarding how ice climbers' biomechanics, specifically spatiotemporal aspects and joint kinematics, relate to performance, particularly in elite athletes. The purpose of this study was to examine the spatiotemporal variables and upper-extremity joint kinematics of ice climbers during a UIAA sanctioned elite lead ice-climbing competition and to assess the relationship between these biomechanical variables and ice climbers' and performance. We hypothesized that higher-performing elite ice climbers would utilize more extended arm position and climb more quickly with fewer moves and longer rests.

2. Materials and Methods

A total of 24 ice climbers participated in this study (16 males, 8 females; age: 36 ± 6.2 years; weight: 69.1 ± 9.6 kg; height: 176.5 ± 8.8 cm). Subjects were recruited from a UIAA-sanctioned elite lead ice-climbing competition and consented to have their competition performance data evaluated. The Fort Lewis College Institutional Review Board approved the protocol for this study, and all competitors provided their written informed consent.

The lead competition was scored based on how high participants ascended the wall in the allotted time of 8 min. If participants reached the same height, time was used to determine finishing rank. All participants attempted the same ice-climbing route, but males and females were scored separately. In addition to their competition ranking, subjects were categorized as the bottom 50% of competitors and top 50% of competitors based on their finishing rank in the male or female division of the competition.

The ice-climbing route consisted of a short ice section, followed by a rock face, and it ended on a man-made feature (Figure 1). Two GoPro Hero 5 cameras (GoPro Inc., San Mateo, CA, USA) recorded at 960 p and 120 Hz from fixed locations on an outcropping in the gorge opposite from the climbing route. The cameras were both positioned at a height at the approximate middle of the analyzed section and were about 30 m in horizontal displacement from the climbing route. To provide left and right vantage points of the entire competition route, each camera was positioned approximately 7 m from the center of the route. All participants completed the bottom portion of the route, which consisted of a non-technical traverse, and few completed the upper man-made feature, so the middle portion above clip 2, which was completed by all competitors, was used for analysis. Within this section, participants consistently used five distinct holds, which were selected for analysis (Figure 1). Most participants used additional holds throughout the analyzed section; however, these holds were not analyzed due to their inconsistent use among competitors.

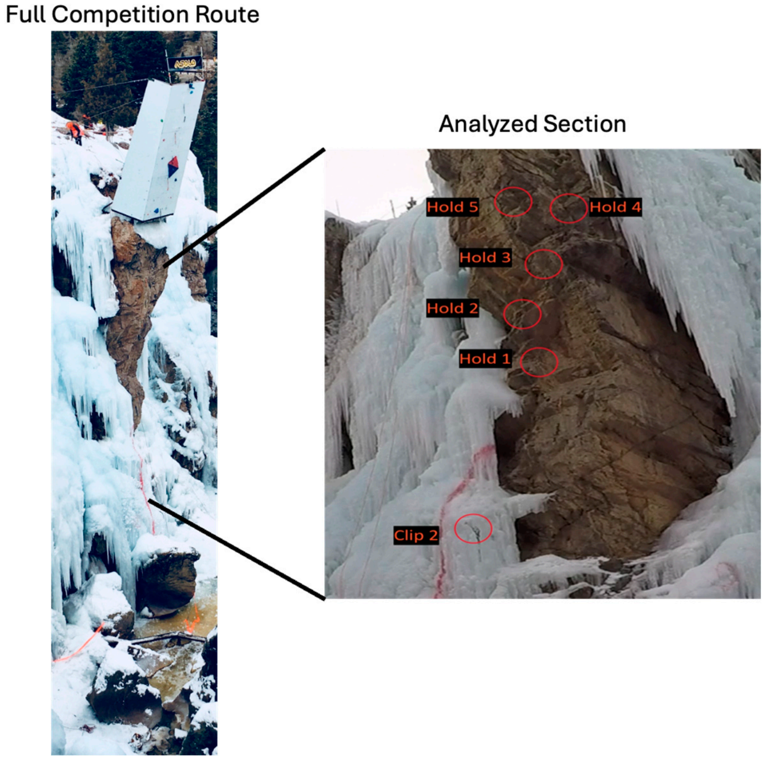

Figure 1. The competition ice-climbing route consisted of a short ice section, followed by a rock face, and it ended on a man-made feature. Five holds located on the middle portion of the route completed by all competitors were used for analysis.

Video data was analyzed with Kinovea motion-analysis software (version 0.8.15). The validity and reliability of using Kinovea to measure joint angles from a variety of angles during athletic activities has been previously established [6,7]. Kinematic measures consisted of each participant's elbow angle (EA) and shoulder angle (SA) at the point of weight bearing on the ice tool. To obtain these joint angle measures, the landmarks of the wrist, elbow, shoulder, and hip of the ipsilateral side of the ice axe being utilized were first identified. The angle tool was then used to mark these anatomical landmarks, which connected these points to form lines representing the forearm, upper arm, and torso body segments. EA was measured as the angle between the forearm (segment from wrist to elbow) and upper arm (segment from elbow to shoulder), and SA was measured as the angle between torso (segment from hip to shoulder) and upper arm (segment from elbow to shoulder). Weight bearing on the ice axe was identified as the moment just before upward movement off a vertically placed ice axe. To determine this point, the researchers identified the frame of video corresponding to the start of the upward movement of the competitor and then reversed by 15 frames (0.125 s). Two researchers first independently identified the points of weight bearing. If the identified frames differed by more than 5%, then the researchers collaboratively identified the point of weight bearing. There were only five instances (4.2%) where the two researchers differed by more than 5%. The same two researchers independently measured the SA and EA of each competitor at the point of weight bearing for holds 1–5. Joint angle measures are the average of the two values obtained by each of the researchers.

Spatiotemporal variables consisted of the time spent climbing ($TIME_{climb}$), which was the duration where the competitor was moving through the analyzed section; the time spent resting ($TIME_{rest}$), which was the duration where the competitor was stationary while climbing the analyzed section; and the total time ($TIME_{total}$), which was the total time for the competitor to move through the analyzed section, i.e., the sum of $TIME_{climb}$ and $TIME_{rest}$. Additional spatiotemporal variables included the number of moves ($COUNT_{move}$) and the number of rests ($COUNT_{rest}$) through the analyzed section. A move was defined as the climber securely contacting the wall with the ice axe or hand, and a rest was considered as a time of no movement that was longer than 2 s in duration.

Pearson correlation coefficients (r) were used to examine the strength of the relationships between SA and EA at holds 1–5. Kendall's coefficient of rank correlation tau-sub-b (τ_B) was used to examine the strength of the relationship between all spatiotemporal variables and competition rank. Paired *t*-tests were used to compare kinematic and spatiotemporal variables between the top and bottom 50% of competitors. Statistical analyses were conducted in JASP (University of Amsterdam, Amsterdam, The Netherlands), and statistical significance was defined as $p \leq 0.05$.

3. Results

3.1. Kinematics

There was a strong positive correlation between SA and EA at hold 1 and moderate positive correlations between SA and EA for holds 2 and 4 (Table 1). This indicates that at the point of weight bearing, elite ice climbers that utilized extended shoulder positions also exhibited extended elbow positions.

Table 1. The relationship between SA and EA at holds 1–5.

Hold	SA (Degrees)	EA (Degrees)	Pearson Correlation Coefficient (r)	*p*-value
1	128.7° ± 18.7	159° ± 14	0.746	<0.001 *
2	137.6° ± 22.8	151.1° ± 16.5	0.538	0.003 *
3	148.9° ± 12.9	167.2° ± 10.7	0.254	0.176
4	139.3° ± 16.8	166.2° ± 12.1	0.613	<0.001 *
5	155.3° ± 15.9	158.9° ± 17.1	0.007	0.972

SA = shoulder angle; EA = elbow angle. * Indicates a statistically significant correlation between shoulder angle and elbow angle; $p \leq 0.05$.

Figure 2 shows a representative example for the relationship between EA and SA for hold 1. There were no significant differences between the top and bottom 50% of elite competitors for EA or SA at any of the holds (all $p > 0.05$). There was a significant correlation between competition rank and EA at hold 2 ($\tau_B = -0.292$, $p = 0.027$); there were no other significant correlations between competition rank and EA or SA.

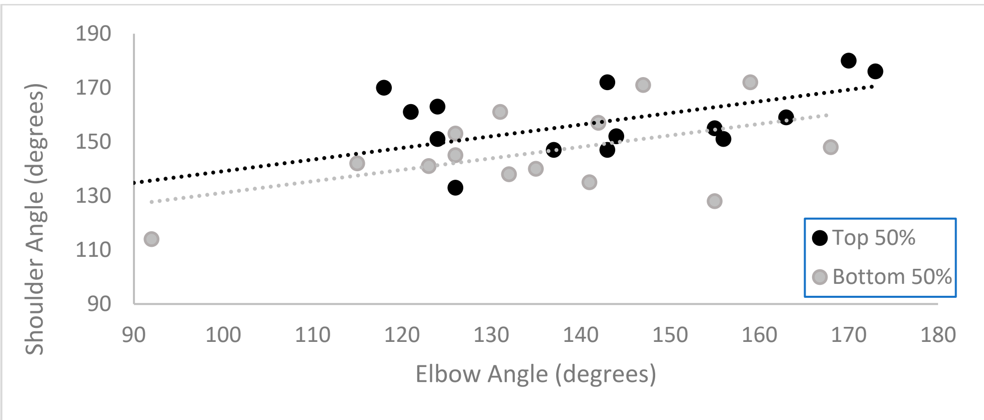

Figure 2. Relationship between hold 1 EA and hold 1 SA for the top and bottom 50% of competitors.

3.2. Spatiotemporal

Table 2 provides the spatiotemporal data for the analyzed section. There was a strong significant correlation between competition rank and $TIME_{total}$ (τ_B = 0.645, $p < 0.001$) and moderate correlations between $TIME_{climb}$ (τ_B = 0.366, p = 0.004) and $TIME_{rest}$ (τ_B = 0.320, p = 0.013), with better-performing competitors moving more quickly through the analyzed section of the climb by climbing faster and using shorter rests. Likewise, $TIME_{total}$, $TIME_{climb}$, and $TIME_{rest}$ were significantly lower for the top 50% of climbers (Figure 3). Additionally, there was a moderate significant correlation between competition rank and the number of moves (τ_B = 0.473, $p < 0.001$), with better-performing competitors using fewer moves through the analyzed section of the climb. Likewise, the top 50% of competitors used significantly fewer moves to climb the analyzed section (Figure 3). The number of rests was not significantly correlated to competition rank and did not differ between the top and bottom 50% of competitors.

Table 2. Spatiotemporal parameters and the relationship with to competition rank.

	All Competitors	Correlation to Competition Rank (τ_B, *p*-value)	Bottom 50%	Top 50%	Difference between Bottom and Top 50% (*p*-value)
$TIME_{climb}$ (s)	90.3 ± 29.3	0.366, p = 0.004	102.5 ± 41.9	76.2 ± 30.3	p = 0.012 *
$TIME_{rest}$ (s)	96.3 ± 29.4	0.320, p = 0.013	114.3 ± 62.4	75.0 ± 38.3	p = 0.025 *
$TIME_{total}$ (s)	186.6 ± 67.1	0.645, $p < 0.001$ ^	232.1 ± 62.9	144.2 ± 36.5	$p < 0.001$ *
$COUNT_{move}$	28.8 ± 8.6	0.473, $p < 0.001$ ^	33.4 ±8.0	23.6 ± 6.1	$p < 0.001$ *
$COUNT_{rest}$	11.9 ± 4.3	0.026, p = 0.844	12.4 ± 4.3	11.4 ± 4.2	p = 0.645

$TIME_{climb}$ = duration where the competitor was moving through the analyzed section; $TIME_{rest}$ = duration where the competitor was stationary while climbing the analyzed section; $TIME_{total}$ = duration to complete the analyzed section ($TIME_{total}$ = $TIME_{climb}$ + $TIME_{rest}$). * Indicates a statistically significant difference between the bottom 50% and top 50% of competitors; $p \leq 0.05$. ^ Indicates a statistically significant correlation (τ_B) with competition rank; $p \leq 0.05$.

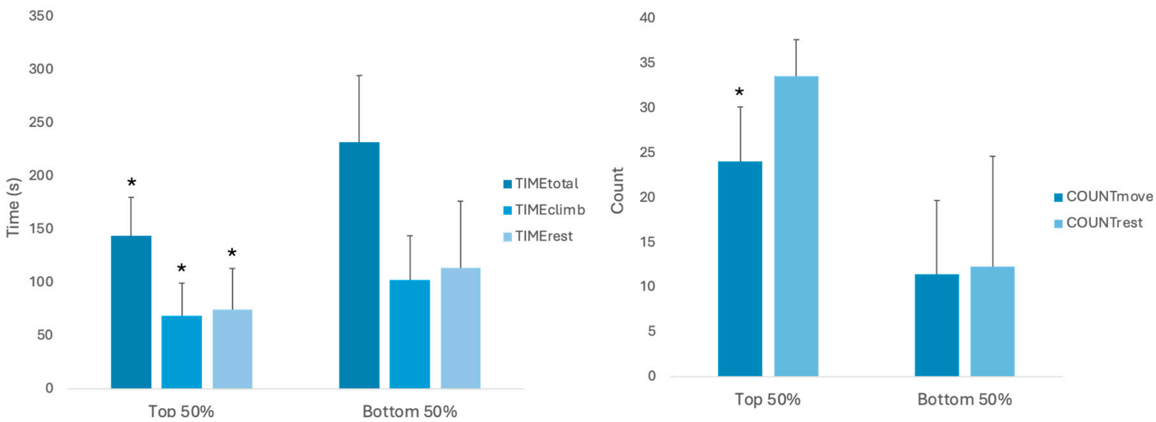

Figure 3. Comparison of spatiotemporal parameters between the top and bottom 50% of competitors. * Indicates a statistically significant difference between the bottom 50% and top 50% of competitors; $p \leq 0.05$.

4. Discussion

The purpose of this study was to examine spatiotemporal variables and upper-extremity joint kinematics of ice climbers' performance during an elite lead ice-climbing competition. We hypothesized that higher-performing elite ice climbers would utilize more extended arm positions and climb more quickly with fewer moves and longer rests. To the best of our knowledge, this is the first study to analyze performance data obtained from an elite ice-climbing competition. In support of our hypothesis, we found significant correlations between competition rank and significant differences between the top and bottom 50% of climbers for $TIME_{total}$, $TIME_{climb}$, and $COUNT_{move}$, indicating that better-performing climbers moved through the analyzed section more quickly by climbing faster with fewer moves. Contrary to our hypothesis, we observed that higher-performing climbers used shorter rest periods ($TIME_{rest}$). Further, as hypothesized, we observed significant correlations between SA and EA for several of the analyzed holds, but there were limited significant relationships between joint kinematics and competition rank and no differences between the top and bottom 50% of competitors in terms of upper-extremity joint kinematics.

Our observation of a significant positive correlation between SA and EA at several of the analyzed holds suggests that there is a coupling of shoulder and elbow extension as climbers bear weight on the ice tool. This extended arm position would require less muscle activation in the upper arm and shoulder [8,9], as it places the load on more passive structures of the skeletal system, such as the bone and ligament, whereas a more flexed upper-extremity position would require greater muscle activation, which would likely lead to more rapid fatigue. Additionally, as was observed in a musculoskeletal model of climbing, the extended upper-extremity position may place the muscle fibers used for climbing closer to their optimum length [10]. The extended arm position also keeps the trunk close to the wall and is associated with lower contact forces in climbing, which are factors that are likely beneficial in ice climbing [11,12].

While our findings showed that elite ice climbers utilized extended arm positions to bear weight on the ice tool, this was not a factor that could distinguish lead climbing performance in this relatively homogenous group of elite climbers. Even though this was not a distinguishing performance factor within an elite group of climbers, this maybe a trainable factor that separates novice and elite climbers. Additionally, we only analyzed the initial point of weight bearing, and there may be additional factors regarding the use of extended arm positions, such as the time spent in an extended position, that may be a better metric to assess performance within elite ice climbers. Furter, EMG analysis would be useful for examining the amount of muscle activation required for different ice-climbing positions.

In climbing, elite climbers rest longer in an isometric position to recover their arms [13] and subsequently need less time to contact the next hold with higher friction compared to novice climbers [12]. Additionally, elite climbers make use of a wider range of upper- and lower-limb moves, resulting in few exploratory moves [1]. Similarly, we found that within an elite group of ice climbers, higher-performing competitors moved more quickly through the competition route and used fewer moves. However, we did not find any relationship between the number of rests and ice-climbing performance, indicating that while the number of rests differs across the performance levels of climbers, within an elite group of ice-climbing competitors, these factors may not be related to performance. It is also important to note that we utilized a section of the competition route that was completed by all climbers, and analysis of a more challenging section of a competition route may provide different results.

The section of the ice-climbing route used for analysis was selected because competitors consistently used distinct holds. This is supported by Seifert et al. [3], who found that elite climbers hooked their ice tools into existing holes and placed their crampons in holes made by the tools, indicating that these holes provided affordances guiding their behavior. The elite competitors in the present study were able to identify these holds as affordances, which likely induced variable upper/lower-limb coordination and allowed them to move more efficiently through the competition route.

The present study is not without limitation. Notably, obtaining data from an actual lead ice-climbing competition provides valuable real-world performance data but limits experimental control. Specifically, it was not possible to obtain 3D joint kinematics because the natural location of the ice-climbing competition limited the camera position. It is also important to note that the fixed camera position, which was not perpendicular to the movement plane, may have resulted in parallax error. Future studies should utilize more controlled laboratory protocols that examine the kinematic and kinetic aspects of ice climbing, including the timing and direction of force application, as well as EMG studies to assess muscle activation. While we succeeded in conducting an analysis of a relatively homogenous group of elite mixed climbers, the variables examined in the present study by no means create an exhaustive list of variables that may be important for performance analysis. Future research examining ice-climbing performance should include additional variables related to performance, particularly lower-extremity kinematics, and utilize more advanced statistical analysis such as regression analysis to obtain a more holistic view of ice-climbing performance.

In conclusion, we found moderate to strong correlations between EA and SA at several of the analyzed holds, indicating that elite ice climbers often utilize an extended arm position when weight bearing in the ice tool during lead climbing. Bearing weight on the ice tool with an extended arm position may require less muscle activation, reduce fatigue, maintain optimal muscle fiber lengths, and keep the trunk close to the wall, with lower contact forces. Future research should examine how utilizing extended arm positions affects muscular dynamics and climbing kinetics. Additionally, we found that higher-performing elite ice climbers ascended faster and with fewer moves, which is likely due to their ability to identify specific holds that provided affordances that guided their movement path.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Research data are available upon request; please contact the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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