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RESEARCH ARTICLE

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# Heel Riser Height Influence on Kinematics and Muscle Activity of Ski Mountaineering: A Field-Based Study

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## ABSTRACT

**Introduction:** The ski binding plays an important role in ski mountaineering. When traveling uphill, the binding has an adjustable heel height known as the riser. Previous laboratory research reported joint kinematics and kinetics are influenced by riser height, however little is known about changes to muscle activity associated with differing joint motion. The purpose of this work was to assess riser height influence on kinematics and muscle activity at different slopes during on-snow skiing.

**Methods:** Three female and nine male recreational ski mountaineers (19-26 y) were tested on 5o and 16o gradients using no riser (0 cm) and riser (5.3 cm) at a submaximal 80% HRmax. Each subject used Backland 85 UL skis and Backland Bindings (Atomic Skis, Altenmarkt, Austria). Subjects skied for 6 min at each binding setting with the last 10 gait-cycles evaluating lower limb joint motion gathered from 2D-sagittal plane motion capture. Electromyography (EMG) collected unilaterally on the rectus femoris, biceps femoris, medial gastrocnemius and triceps brachii also.

**Results:** 5o slope: hip range of motion [ROM] decreased (p = .003), ankle ROM decreased (p =.005), stride length decreased (p = .004), RPE increased (p = .02) for riser compared to no riser. At 16o slope: hip ROM decreased (p = .001), and Rating of perceived exertion [RPE] decreased (p =.004) for riser compared to no riser. HR, glide distance, velocity, EMG, and net mechanical efficiency were not different between riser heights on either slope.

**Conclusion:** Lower body joint kinematics, step length and RPE varied significantly with riser height. Kinematic differences did not impact velocity or muscle activity when controlling pace. These results agree with previous findings showing minimal differences in EMG and HR while lower body kinematics and RPE changed with riser height.

## ARTICLE HISTORY

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## Introduction

Ski mountaineering (skimo) is a popular outdoor activity that combines skiing and mountaineering, allowing skiers to explore backcountry terrain that is usually inaccessible by lift systems. Ski mountaineers often encounter steep and challenging terrain that requires adjustments to their equipment to optimize performance and safety [1, 2]. One of the key components of skimo equipment is the binding, which connects the skier's boot to the ski. Most skimo bindings are designed with a heel riser, which allows the skier to choose the height of their heel above the ski during the stance phase of uphill walking. Usage of the riser height is typically made on personal preference and slope gradient.

Recreational skimo is a strenuous endurance exercise which places high importance on comfort and efficiency to sustain this endurance exercise [3, 4]. Previous research has shown that in skimo competitions, skiers maintain 80% heart rate max [HRmax] during skimo races [2]. It has also been found that vertical energy cost was lowest when skiers skied straight, rather than zigzagging, up steeper slope gradients, under greater speeds for less duration than traveling to the same elevation using shallower slopes [3, 4]. This suggests that skimo participants may be more efficient by ascending steeper slopes more quickly to optimize vertical energy cost.

With reduced vertical energy cost on steeper slopes, the use of a riser may be an important aspect to consider in the performance-equipment interaction of skimo efficiency. The riser was developed with the intention for improving comfort and efficiency when ascending steep slopes [5, 6]. However, riser height preferences can vary greatly between skiers. It has been shown by Haselbacher et al., that skimo competitors rarely use their risers in competition settings, whereas recreational users tend to use their risers more frequently [7]. Recreational skimo skiers often use risers as it provides those skiers increased subjective comfort. This could be due to two main factors: 1) riser use may affect lower body kinematics which may reduce range of motion (ROM) to more normal uphill walking ranges, and 2) this ROM change may alter

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muscle activity of primary uphill walking muscles such as the rectus femoris, biceps femoris and gastrocnemius.

To date, only one study has evaluated the effect of riser height on lower body kinematics during skimo in a laboratory setting [5]. As heel riser height increased, ROM of the hip, knee, and ankle decreased during the gait cycle. While these studies suggest kinematics and kinetics may be affected by riser height, there is a well-known discrepancy that can occur between treadmill ski research and field-based research through Nordic skiing studies [8]. Though treadmill research does have the benefits of controlled velocity and environmental conditions, the main outcome variable, which is extremely difficult to mimic on a treadmill, is glide. Gliding in skimo may be greater on snow compared to on a treadmill, which may further influence kinematics, muscle activity or spatiotemporal gait metrics. To date, there have been no studies published on how heel riser height effects lower body kinematics and muscle activity while skiing on snow.

Therefore, the purpose of this study was to assess the effect of heel riser height on lower body kinematics, spatiotemporal gait metrics and muscle activity during skimo on snow, where glide may be greater. Our hypothesis was that as riser height increases, lower body kinematics will decrease on both a flatter slope, and a steep incline slope. We also hypothesized that on the flatter slope, high riser height would increase muscle activity of the rectus femoris, biceps femoris, medial gastrocnemius, and triceps brachii, whereas on the steep slope, muscle activity would be greater under the no riser condition. A secondary purpose was to investigate kinematics at a self- selected pace.

## Methods

### Participants

Fourteen experienced recreational backcountry skiers participated in this study. (Mean age: 23 ± 4.3 years, height: 1.79 ± .28 m, weight: 75.4 ± 19.2 kg, boot size (mondo): 26.5 ± 2.5, VO2max: 4.2 ± 0.85 L*min$^{-1}$, 54 ± 9 ml*kg-1*min$^{-1}$, HRmax: 198 ± 4 bpm). All participants used their own slope boots set to walk-mode. Inclusion criteria for the study was defined as at least 3 years of backcountry skiing experience, with at least 15 days of skimo per season. Participants were excluded if minimum experience was not met, if the participant had any present injuries or illness, and if the participant was a competitive skimo athlete. The ethics of methods and procedures were approved by the Institutional Review Board of Montana State University, Office of Research and Compliance.

### Data Collection

### Part 1 – Controlled HR intensity of 160 bpm, on 5° and 16° incline

The initial visit was used to establish a baseline, participants came into the laboratory to measure anthropometrics and obtain maximal oxygen uptake (VO2max). The VO2max test was performed using the Bruce protocol on a treadmill, using a Parvomedics Metabolic Cart to measure oxygen consumption (Parvomedics, Salt Lake City, UT).

On snow, trials were analyzed on two different slopes, a 5° and 16°. Riser heights were 0.0 cm (no riser) and 5.3 cm of heel lift (riser). The participants skied uphill on both gradients for 6 minute trials under randomized order of riser heights. The snow quality was groomed, packed snow. Temperatures ranged from -10 to 4o C. If HR was not within 7 bpm of 160 bpm, approximately their 80% HRmax, subjects repeated that trial. All skiers began the trials on the flatter slope to minimize the influence of fatigue.

### Part 2 – Self-selected pace (SSP) on 5° incline

A sub-group of six participants which participated in the initial protocol were asked to return for a secondary study. All participants from Part 1 were contacted, however only six volunteered to return for Part 2 due to availability and time of data collection. The participants skied only on the flatter slope, using the same protocol and measurements, excluding muscle activity measurements as in Part 1, then repeating the flatter slope using a self-selected pace for both riser conditions.

The instructions for self-selected pace were to ski at their comfortable pace for a 1 hr recreational skimo exercise. Heart rate was collected at the end of each trial. Kinematics were captured identically to Part 1 of data collection.

### Equipment/Measurements

The subjects were fitted with Atomic Backland 85 UL Skis (179 cm length) and Atomic Backland bindings adjusted to securely fit the participant's skimo boot. (Atomic Austria GMBH, Altenmarkt, Austria). To measure heart rate, each subject was fitted with a Polar HR Chest Monitor and wristwatch. Rating of Perceived Exertion (RPE) was measured at the end of each trial using the Borg 6-20 scale. Sagittal plane kinematics was recorded using a Sony HD 4k Camera. Motion capture was recorded for the last 10 gait cycles of each trial on both 5°and 16° slopes. Calibration was performed every 3 gait-cycles to reduce parallax error. To identify body segments, reflective markers were placed unilaterally on the acromion process, greater trochanter, lateral epicondyle, lateral malleolus, and head of the 5th metatarsal. Although difficult to identify specific landmarks within the ski boot, the lateral malleolus has been shown to appear quite accurately at the hinge pivot of the boot, and head of the 5th metatarsal was tapped through the boot. Additionally, due to clothing constraints to withstand cold temperatures, elastic bandages were wrapped around clothing near markers to secure the markers as best as possible.

To measure muscle activity, electromyography (EMG) surface electrodes were placed unilaterally on the triceps brachii, rectus femoris, biceps femoris, and medial gastrocnemius. The triceps brachii was investigated as riser may influence upper body kinematics. Skin was shaved and cleaned with alcohol wipes before placing all sensors (4-bar bipolar electrode with 5 mm interelectrode spacing, Delsys Inc., Natick, MA, USA). Sensors were placed in line with pennation angle over the belly of the muscle at the midpoint in accordance with Rainoldi et al. [9].

### Data Processing

To process kinematic data, Tracker (version 6.1.5, Open Source Physics, USA) motion capture software was used to manually digitize marker trajectories into XY for each trial. The distances were calibrated using the outside ski, which had a tip-to-tail length: 1.791 m. A custom MATLAB Script was used to then calculate segment lengths for the foot, shank, thigh, and torso which were then used through Law of Cosines to calculate joint angles for the ankle, knee, and hip. Joint angles were smoothed using Bandpass Butterworth Filter.

To analyze spatiotemporal gait parametric data, Tracker was also used. Stride length, glide distance, stride rate and velocity were defined and measured using 2D motion capture. To measure glide distance, glide had to be defined. While one study analyzed foot loading patterns using insole force gauges Haselbacher et al., no published studies in skimo have attempted to define gliding from the sagittal plane [7]. However, Cross-country skiing studies have previously defined a rolling phase during roller skiing [10]. Glide was identified in the 2D sagittal plane similar to the rolling phase which occurs during roller skiing. Glide was therefore defined as the point in which the trailing limb moves into the swing phase of the gait cycle. At this point, the leading limb may achieve forward displacement, which was measured from the ankle hinge of the ski boot. In all trials, termination of glide occurred when the non-supporting limb achieved heel contact to generate an additional force.

Stride length was defined as the total distance of the left boot ankle hinge from the beginning left leg toe-off to right leg toe-off. It is important to note that glide may have occurred during this timeframe, however it was determined that measuring both glide and stride length could help identify how risers may affect different aspects of the skimo gait. Step rate was defined as the time to the thousandth of a second to complete one step, which was defined above from step length. Velocity was found by dividing the distance covered in 5 gait cycles (left leg heel contact- left leg heel contact) by the left lateral boot hinge by the time to complete that distance.

Analog EMG signals were amplified at the source and recorded at 1926 Hz (Trigno Personal Monitor, Delsys Inc., Natick, MA, USA). EMG signals were filtered using a zero-phase 4th order B and pass Butterworth filter with cutoff frequencies of 20 Hz to 400 Hz. To determine cutoff frequencies, a residual analysis of 95% signal power was retained. Filtered signals were rectified and smoothed a using a root mean square analysis (125 ms window, 25 ms window overlap).

**Peak and average RMS were calculated for every gait cycle.**

## Statistics

To assess for differences between riser conditions on both slope gradients, a pairwise comparison t-test was performed to assess to differences in riser height for all dependent variables. For all tests, an alpha level .05 was used to determine significant results with an effect size scale: small < .2, .2 < medium < .5, large > .5. To correct for Type 1 Error when performing numerous paired t- tests, the Holm Method was applied to adjust significance level in ranking from smallest to largest p-values [11]. All statistical tests were performed using SPSS (IBM Corp. SPSS Statistics for Windows, NY: IBM Corp).

| Anthropometrics and Bruce Protocol measurements | value |
|---|---|
| Age | 23 ± 4.3(years) |
| Height | 1.79 ± .28 (m) |
| Weight | 75.4 ± 19.2(kg) |
| Boot Size | 26.5 ± 2.5 (mondo) |
| $VO2_{max}$ | 4.2 ± 0.85 $L*min^{-1}$ |
| $VO2_{max}$ | 54 ± 9 $ml*kg^{-1}*min^{-1}$ |
| HRmax Anthropometrics provide subjects size, age, mass, fitness level. | 198 ± 4 (bpm) an index of the and respective |

**Part 1:** Controlled HR intensity of 160 bpm, on 5° and 16° incline

There were differences between riser and no riser on flatter slope. Using riser was found to decrease lower body range of motion in the hip (5%, large effect size), ankle (28%, large effect size), stride length (6%, medium effect size) compared to no riser. RPE was also found to be increase in riser by 15%, compared to no riser. There were no differences between riser and no riser for muscle activity (MG, BF, RF, TB, p > .05, small effect sizes), velocity, HR, and both relative and absolute glide (Table 1).

**Table 1:** Flat (controlled intensity). Variables are ordered from the smallest to largest p- value. * Indicates difference between variables. Hip ROM, Knee ROM and Ankle ROM were greater with no riser. RPE and stride rate were greater for riser. Stride length was greater for no reason

| Flat (80% HRmax) | Riser Setting | Means ± SD | p-value (holm correction) | Cohen's D |
|---|---|---|---|---|
| RPE (6-20 Borg) | no riser riser | 11.82 ± 1.54<br>13.63 ± 1.36 | .01* | 1.41 |
| Hip ROM (degrees) | no riser riser | 65.8 ± 13.0<br>62.3 ± 7.5 | .013* | 1.64 |
| Stride Length (%BH) | no riser riser | 59.0 ± 8.6<br>55.6 ± 9.0 | .012* | 0.61 |
| Ankle ROM (degrees) | no riser riser | 36.01 ± 8.14<br>25.94 ± 4.98 | .008* | 0.47 |
| Knee ROM (degrees) | no riser riser | 36.4 ± 6.3<br>32.2 ± 6.4 | .025* | 0.46 |
| Stride Rate (step/min) | no riser riser | 41.4 ± 6.3<br>42.92 ± 7.1 | .032* | 0.25 |
| Glide (m) | no riser riser | 0.15 ± 0.06<br>0.13 ± 0.05 | 0.23 | 0.11 |
| Glide (%BH) | no riser riser | 7.94 ± 3.26<br>6.83 ± 2.78 | 0.15 | 0.22 |
| HR (bpm) | no riser riser | 161 ± 4<br>162 ± 5 | 0.09 | 0.47 |
| Velocity (m/s) | no riser riser | 1.41 ± 0.35<br>1.39 ± 0.24 | 0.07 | 0.11 |

Using the riser also influenced kinematics and gait metrics on 16o at a controlled intensity. Riser decreased ROM at the hip (13%, large effect size) and RPE (13%, large effect size) compared to no riser. There were no differences between riser and no riser for muscle activity (MG, BF, RF, TB, p > .05, small effect sizes), velocity, HR, and both stride length and stride rate (Table 2).

**Table 2:** Steep at controlled intensity of 80% HRmax. Variables are ordered from smallest to largest p-value. * Indicates difference between variables. Hip ROM and RPE were greater for no riser. No other differences were found

| Steep (80% HRmax) | Riser Setting | Mean ± SD | Holm Correction | Cohen's D |
|---|---|---|---|---|
| Hip ROM (degrees) | no riser riser | 70.63 ± 9.14<br>61.46 ± 7.81 | 0.008* | 0.96 |
| RPE (Borg 6-20) | no riser riser | 16.38 ± 1.19<br>14.34 ± 1.09 | 0.035* | 1.26 |
| Ankle ROM (degrees) | no riser riser | 29.2 ± 6.73<br>25.4 ± 6.55 | 0.126 | 0.56 |
| HR (bpm) | no riser riser | 162 ± 3<br>161 ± 4 | 0.237 | 0.21 |
| Stride Rate (step/min) | no riser riser | 35.97 ± 5.25<br>37.43 ± 5.51 | 0.258 | 0.278 |
| Stride Length (%BH) | no riser riser | 37.76 ± 4.75<br>37.0 ± 5.03 | 0.215 | 0.14 |
| Velocity (m/s) | no riser riser | 1.17 ± 0.45<br>1.15 ± 0.42 | 0.191 | 0.033 |
| Knee ROM (degrees) | no riser riser | 39.9 ± 4.01<br>39.62 ± 7.09 | 0.111 | 0.04 |

### Part 2 – Self-selected pace on 5° incline

For the self-selected pace group on flatter slope, an effect of riser was also found. Using riser resulted in increased HR by (4%, large effect size) and RPE (12%, large effect size) compared to no riser. There were no differences in hip, knee, and ankle ROM nor for the gait characteristics (Table 3).

**Table 3:** Flat pitch, self-selected pace. * Indicates significance. HR was greater for riser, and RPE was greater for riser.

| Flat (self-selected) | Riser Setting | Mean ± SD | Holm Correction | Cohen's D |
|---|---|---|---|---|
| Hip ROM (degrees) | no riser riser | 165 ±3<br>173 ± 4 | 0.02* | 1.41 |
| RPE (6-20 Borg) | no riser riser | 15.07 ± 0.7<br>17 ± 0.8 | 0.0225* | 1.64 |
| Stride Length (%BH) | no riser riser | 58.7 ± 6.4<br>53.8 ± 8.9 | 0.053* | 0.61 |
| Glide (%BH) | no riser riser | 8.62 ± 4.1<br>6.83 ± 3.6 | 0.07* | 0.47 |
| Glide (m) | no riser riser | 0.16 ± 0.1<br>0.13 ± 0.1 | 0.048* | 0.46 |
| Velocity (m/s) | no riser riser | 1.61 ± 0.1<br>1.65 ± 0.2 | 0.167* | 0.25 |
| Step rate (step/sec) | no riser riser | 1.19 ± 0.2<br>1.18 ± 0.1 | 0.171 | 0.11 |
| Ankle ROM (deg.) | no riser riser | 21.2 ± 4.4<br>20.2 ± 3.9 | 0.15 | 0.22 |
| Knee ROM (deg.) | no riser riser | 37.5 ± 9.2<br>38.3 ± 7.6 | 0.095 | 0.47 |
| Hip ROM (deg.) | no riser riser | 44.2 ± 5.3<br>45.3 ± 7.5 | 0.054 | 0.11 |

## Discussion

The purpose of this study was to measure the effect of heel riser height on lower body kinematics, spatiotemporal gait metrics and muscle activity on two different slopes. The secondary purpose was to measure the effect of heel riser height on lower body kinematics and spatiotemporal gait metrics on a flatter slope at self-selected pace on a flatter slope.

On the flatter slope at the controlled intensity, the results supported our hypothesis for hip ROM, ankle ROM, and stride length being significantly lower in riser compared to no riser. The kinematic results can be explained as using riser on the flatter slope places the ankle in a more plantar flexed position, which places the body's COM in a more anterior position. The overall decrease in step length appears to be caused by a decrease in joint ROM, as reduced hip ROM and ankle ROM would shorten the total stride of a skier. We found that RPE increased in riser compared to no riser. One possibility is that decreased ROM in the hip, knee, and ankle placed the body in an unlearned movement pattern which would increase muscle spindle feedback signals, which may increase effort to generate muscle activation patterns to promote a similar movement to skiing on the flatter slope with no riser. These findings were very similar to previous research in a laboratory [5].

No differences were found in velocity, stride rate, or glide between riser and no riser on the flatter slope. While hypothesized that glide would decrease in riser compared no riser on flatter slope, we found that there was no difference in glide distance and therefore, the observed decrease in step length was mainly due to a decrease in lower body ROM. One explanation for glide not being different between the two riser conditions could be the overall magnitude of glide in the skimo study compared to Nordic Skiing studies. Cross-country skiing gliding (rolling) on flatter slopes is generally around 1.0 m while the observed glide distance of this study revealed glide distances of 0.02 m at most [12]. This smaller magnitude could show that the greater amount of friction caused by the skin is not necessarily affected by riser height. While glide is a component on snow during skimo on flatter slopes, which was not observed in treadmill studies riser setting, did not influence glide distance [5].

Using riser was shown to decrease hip ROM and RPE on steep compared to no riser. When walking up steep slopes, an elevated heel during stance would place the ankle in a plantar flexed position. The boot ROM may play an effect on kinematics as skimo boot ROM is limited compared to ankle ROM. This restriction of movement in the boot may lead to an adjustment in hip ROM when walking up steeper slopes. This is further supported as a difference in ankle ROM was not found between riser and no riser on steep. Similar results were supported by previous research, where at both low and high inclines on a treadmill there was a decrease in hip ROM as riser height increased [13].

RPE was found to be lower in riser compared to no riser. This appears to be an effect of ROM as HR, gait characteristics, and muscle activity was not different between riser and no riser on steep. This could be explained by normalizing the movement to a position in which is a more learned movement pattern as the riser elevates the heel from the ski, allowing the foot to be in a similar position to walking up steps, whereas no riser places the ankle in a dorsiflexed position during the stance phase on steep slopes.

These results were similar to a previous study which found that while muscle activity and metabolic rate remained similar, RPE increased [6]. As ankle dorsiflexion normative ranges have been shown to be 10-20°, skiing up a 16° slope would place the ankle at the upper range of normal ROM [14]. A secondary factor could be that boot dorsiflexion ROM limits this further, requiring changes in hip ROM to compensate for the lack of ankle movement.

We observed no differences in HR, stride rate, stride length, or velocity. As expected, there was no difference in HR, however we did expect to see a decrease in velocity in no riser, as it is thought to be more difficult than using a riser during the steep ascent. These results are similar to the treadmill study by, in which the differences in RPE were greater at the lowest riser setting, but physiological differences were minimal. It appears that riser on steep slopes may have an effect of comfort in altering kinematics. We observed no difference in stride length for riser, which we did not expect given hip ROM and ankle ROM were lower in riser [6].

This may be due to smaller magnitudes of decrease in ROM on steep compared to flatter slopes, where total combined ROM was only 12° on steep compared to 18° on flatter. Twelve degrees on steep (ST) may not be enough to see large differences in step length.

For the SSP sub-group in Part 2, our findings were quite the opposite, as we found HR and RPE increased in riser compared to no riser. We found no differences in lower body ROM or gait characteristics. There are several key comparisons to make in these results compared to the controlled pace on flatter slopes in Part 1. First, both HR and RPE were greater in riser than no riser, so there were comfort and cardiovascular, as possibly, metabolic differences between the riser conditions. Subjects skied at an approximate 85% HRmax in riser compared to 80% HRmax in no riser. Over long durations, this difference in HR intensity could lead to metabolic differences between riser conditions.

As for the kinematics in SSP, our findings were very different compared to the results from Part:

For SSP, there were no differences in lower body ROM, or gait characteristics between riser and no riser. This may suggest that when allowed self-selecting pace using risers subjects showed a preference toward maintaining a learned movement pattern through normalizing lower body ROM, even though it appeared to increase HR and RPE compared to no riser. This is very different from Part 1 on flatter slopes, where hip and ankle ROM decreased in riser compared to no riser, but HR was not different. The maintenance of ROM between riser and no riser could further explain why gait characteristics were not different.

There were no observed differences in muscle activity for RF, BF, MG, or TB on flatter slopes between riser and no riser. These findings moderately agree with one laboratory study by which showed no increase changes in muscle activity for RF, BF or MG on 8%, 16% and 24% gradients as an effect of riser only [6]. When performing an analysis of variance (ANOVA), they did find increased BF and MG activity with no riser as an interaction effect of slope gradient and riser height. It appears that risers have a minimal effect on muscle activity through EMG even though lower body kinematics are altered. Contrary to our hypothesis we also found no difference in muscle activity for the triceps brachii. In a previous laboratory study, it was found that riser height had an effect on vertical pole loading force. While it was thought that this increase in vertical pole loading may increase TB activity, on snow, there was no increase in TB activity as an effect of riser.

We did not collect metabolic data in this study. Without metabolic data, energy cost of locomotion of all riser settings could not be calculated. Metabolic data was not collected as proper equipment for field-based measurements were unavailable. While heart rate and velocity were not different in Part 1, there may still be a difference in energy cost when metabolic data is a factor. One study found that only at 8% (4.6o) gradient, energy cost was greater using a high riser compared to a low riser. This may be an area of future study as not much is currently known about riser position influence on energy cost on snow [6].

Another limitation to consider is that subjects used their own ski boots. This may impact range of motion as range of motion at the ankle joint can vary depending on boot type and if the boot was in walk-mode. All subjects' boots in the study used their respective walk-mode to allow for the greatest ROM available. When comparing range of motion in walk mode across touring specific boots, ROM varies by approximately 5o. There is currently no literature on the impact of ski boot range of motion on kinematics and muscle activity to draw suggestions as to how this may have influenced our data.

Given these mixed effects of riser height during paced and self-paced skiing, it is important to highlight the varying response to riser height under a controlled intensity compared to SSP. The effect of heel riser at controlled intensities was very similar to the previous treadmill study

assessing effect of heel riser, showing decreased lower body ROM under same the velocity and workload [5]. When subjects were allowed to ski at SSP, they skied again at the same velocity, maintained a similar lower body ROM, but worked at a greater HR and RPE to achieve this. When considering the implications of these findings, it is important to highlight that the recreational skimo participants responded differently to riser between controlled pace and self-selected pace. Determining the application and methodology in future studies may be critical to further understand performance-equipment interaction in skimo. Further studies may also benefit from measuring how elite skimo athletes respond between self-selected pace and controlled pace. Other key findings from our study were that at a short-duration, controlled intensity, riser height influences primarily kinematics and RPE. From these results it appears that physiologically there may not be many large differences in heel riser height, but biomechanically, the change in kinematics alters the perceived exertion between risers for recreational ski- mountaineers [14].

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## Competing interests

The author/s has/have declared that no competing interests exist.

## Data availability statement

All relevant data are within the paper

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