Sport Sciences for Health (2024) 20:975–982
https://doi.org/10.1007/s11332-024-01191-y

RESEARCH

Effects of slight ski boot weight variations on ski mountaineering energy cost and mechanical work at race intensity

Lorenzo Bortolan[1,2] · Aldo Savoldelli[1,3] · Alessandro Fornasiero[1,2] · Sofia Nanni[2] · Laura Gazzi[2] · Marco Decet[1,4] · Chiara Zoppirolli[1,2] · Federico Schena[1,4] · Barbara Pellegrini[1,2]

Received: 11 August 2023 / Accepted: 5 March 2024 / Published online: 22 March 2024

Abstract

Purpose Uphill ski mountaineering performance appears to be related to metabolic cost of locomotion and skiers' weight. The present study aimed to evaluate the effects of slight variations in equipment weight on metabolic and mechanical work (MW) of ski mountaineering, at race pace.

Methods Thirteen male ski mountaineers were asked to ski on a treadmill at 25% slope and 80% of their maximal aerobic speed. They completed four 5-min bouts with additional weights of 0 kg (control), 0.2 kg, 0.4 kg, and 0.6 kg added to each ski boot in a blind mode and random order. Ski mountaineering energy cost (EC) was determined by gas exchange measurements, while MW was determined from the changes in the mechanical energy of body centre of mass (COM), body segments and equipment.

Results EC and total MW were significantly (all $p < 0.001$) and largely ($\eta^2 = 0.712$ and $\eta^2 = 0.704$, respectively) increased for every 0.2 kg of mass added, by around 2% and 1%, respectively. The increase in the MW was related to a significant increase in the work needed to lift the weight against gravity and to the increased work done to move the segments of the lower body with respect to COM.

Conclusion The present investigation shows that even small increments in racing gear weight are associated with an increase in ski mountaineering EC, possibly leading to a consequent decreased performance on uphill terrains.

Keywords Performance · Elite · Winter Olympic Sport · Sports equipment

Introduction

Ski mountaineering is a winter sport that involves alternately climbing and descending snowy slopes and can be practiced either for recreational or competitive purposes.

Official ski mountaineering competitions are regulated by the ISMF (International Ski Mountaineering Federation). These races are divided into five different racing formats that differ primarily in total vertical gain, total distance, and the distribution of downhill and uphill sections. The traditional ski mountaineering competitions consist of individual and team races, requiring a minimum of three climbs and descents and lasting less than 3 h [1]. More recently, in 2007, vertical races have been introduced. These races involve climbing a single slope with no downhill section, placing the greatest emphasis on the ability to ski uphill. Ski mountaineering, featuring the disciplines of sprint and mixed relay, will debut at the Olympic Winter Games in Milano-Cortina 2026. While ski mountaineering races typically adhere to a mass start format, sprint races involve a qualification stage contested with individual time trials, followed by quarterfinals, semifinals, and a final heat contested by groups of skiers in heats. The mixed relay comprises a time trial qualification and a final heat.

This sport generally requires both pronounced physiological capacity when skiing uphill [2, 3] and remarkable downhill skiing skills. Ski mountaineering performance has been

✉ Lorenzo Bortolan
lorenzo.bortolan@univr.it

1 CeRiSM, Sport Mountain and Health Research Centre, University of Verona, Rovereto, Italy

2 Department of Engineering for Innovation Medicine, University of Verona, Verona, Italy

3 Department of Cellular, Computational and Integrative Biology (CIBIO), University of Trento, Trento, Italy

4 Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy

generally related to athletes' maximal oxygen consumption (VO_{2max}) and the oxygen consumption at the ventilatory thresholds (VT1 and VT2) relative to body mass (i.e., mL/min/kg) [2]. Specifically, around 80% of uphill performance variation in a vertical race could be explained by differences in oxygen consumption at VT2, scaled for body mass [4]. Furthermore, a negative correlation between race time and fat mass and body fat percentage [3, 4] has been found.

The negative impact of weight on performance pertains not only to the athlete's body weight but also to the weight of the equipment. As a consequence, it is a common practice among athletes to reduce the weight of the equipment as much as possible. In ski mountaineering, to prevent an excessive reduction of materials, structural weakening and potential safety issues, the international federation has set minimum weights for skis and bindings (1560 and 1460 g for males and females, respectively) and boots (1000 and 900 g for males and females, respectively) per pair [5, 6].

Despite this attention to the equipment weight, its actual effect on ski mountaineering performance is not fully known. Previous research in ski mountaineering has shown that an increase in boot/binding/ankle weight have a negative effect on energy cost (EC) by 1–6% [7, 8]. However, these studies utilized higher weight changes and lower testing speeds compared to competitive scenarios. In addition, in previous experiments the subjects were not blinded. This most likely influenced the subjects' responses and perceptions as observed in other sports [9]. These factors highlight the need for further investigations.

Even if the evaluation of the effects of weight on EC alone could be of interest, a further relevant information is constituted by deepening the mechanisms that lead to this worsening. For this purpose, it is useful to account for the augmented mechanical work (MW) to transport and lift the additional weight. By investigating the effect of adding weight in running on both metabolic and MW, it was found that changes in oxygen consumption were directly proportional to the changes in MW done on the leg [10].

The effect of extra weight on positive MW sustained by the athlete depends by factors like the direction of movement with respect to gravity, that is the inclination of the terrain (downhill, flat, uphill) and by the position of the added mass (proximal or distal) on the body. From a mechanical point of view indeed in the case of weight added to a distal segment, the mechanical workload increases both for the need to raise against gravity and to accelerate the mass at each step. This translate in a worse movement economy, as it has been demonstrated that it is approximately six times more expensive to carry a given mass on the feet or ankles compared to the back [11]. This suggests that even a relatively small mass in relation to the total weight of skiers, could potentially have a negative impact on MW done by the skiers and then on the cost of locomotion.

Therefore, the present investigation was designed to evaluate the effect of a blind and slight variation in competitive equipment weight on ski mountaineering metabolic and MW at race intensity. Our goal here was to try to understand whether variations in the weight of the boots can have an effect on uphill performance. Considering the minimal weight increment introduced in this study our hypothesis was that the metabolic cost would not change significantly. Conversely, due to the distal position of the added mass, we expect a notable increase in the MW required for lower leg movement.

Methods

Subjects

Thirteen male ski mountaineers (age 28 ± 9 years, stature 1.74 ± 0.03 m, body mass: 67.5 ± 4.4 kg) participated in the study. All participants were experienced ski mountaineers, familiar with treadmill testing and the equipment, and were training regularly and participating in competitions at the time of the study. Their VO_{2max}, determined during an incremental test to exhaustion described in detail below was 67.1 ± 5.2 (mL min^{-1} kg^{-1}).

Prior to the study, all the participants were informed about the testing protocols and provided their written informed consent. The study was performed in accordance with the principles of the Declaration of Helsinki and the protocol was approved by the departmental ethical committee (Approval Committee for Research on the Person, protocol n. 41.R1/2021).

Overall design and skiing equipment

Measurements were performed on a motorized treadmill with a belt surface 2.5 m wide and 3.5 m long (RL3500E; Rodby, Vange, Sweden). All subjects used the same pair of skis (RSR, La Sportiva, Ziano di Fiemme, Italy), bindings (La Sportiva, Ziano di Fiemme, Italy) and skins (Pomoca Race Pro 2.0, Oberalp Group, Bolzano, Italy). Skis length was 160 cm while skis and bindings weight was 1966 g. The subject wore the same model of full carbon frame ski boot (Stratos V, La Sportiva, Ziano di Fiemme, Italy) size 42, weight 525 g each boot. This exceeded the minimum weight specified by federal rules by 25 g per pair. All athletes used the same pair of ski poles (Gabel, Rosà, Italy) weighing 300 g each pole, which were adjustable in length, allowing each subject to select his preferred length.

Before the tests, the participants warmed up for about 10 min by skiing at low intensity, with a speed of 3.5 km h^{-1} and slope of 25%. The subjects underwent an incremental test to exhaustion at a constant slope of 25%

starting at a speed of 3.6 km h^{-1} with speed increases of 0.6 km h^{-1} for each step, lasting 3 min each, until volitional exhaustion.

Subjects then underwent four bouts in a single blind manner and in a random order, with weights of 0 kg, 0.2 kg, 0.4 kg, and 0.6 kg added to each ski boot. One or more lead bars weighing 0.2 kg each were fixed to the central part of the boot soles using adhesive tape. To blind the condition of zero added weight to the subject, a piece of polystyrene of the same size as the bars was used. To impose the effort actually attained during a vertical race [4] the slope was set at 25% and the speed was set for each subject at 80% of the maximum speed achieved during the incremental test rounded to 0.2 km h^{-1}, which corresponds to the minimum allowed variation by the treadmill [4].

Each bout lasted for 5 min and was followed by 5 min of passive recovery, which allowed the subject to rest and the experimenters to vary the weight applied to the boots. The first bout was preceded by a warm up of similar intensity and duration of the trials. To maintain the technique as homogeneous as possible, the athletes were asked to employ a diagonal technique that involves moving the lower limb and the contralateral upper limb simultaneously. Respiratory gas exchange and heart rate were measured continuously during the entire session, and kinematic data were acquired for 30 s starting at min 4. The rating of perceived exertion using Borg's Category Ratio Scale 0–100 (CR-100) and blood lactate were collected at the end of each trial.

Measurements and analysis of metabolic data

Respiratory gas exchange values were measured by means of a breath-by-breath metabolic cart (Cosmed Quark CPET, Rome, Italy) calibrated before each test according to the manufacturer instruction.

A peripheral blood sample was taken from the ear lobe and collected in a 25 µL capillary tube. Blood lactate concentration [BLa] was measured using a Biosen C-line blood lactate analyzer (EKF Diagnostic, GmbH, Magdeburg, Germany).

The average oxygen uptake ($V'O_2$), ventilation (VE), and heart rate (HR) attained during the final 120 s of each trial were calculated. The rate of metabolic energy expenditure was calculated by multiplying the values of oxygen uptake ($V'O_2$) by the energetic equivalent for oxygen, which is specifically related to the respiratory quotient value [12] The EC of skiing (expressed in J m^{-1} kg^{-1}) was calculated by dividing the rate of metabolic energy expenditure by the skiing speed and was normalized by body weight. Metabolic calculations were carried out using Excel 365 (Microsoft Corporation, Redmond, WA, USA).

Measurements and analysis of kinematic data

Kinematic data were acquired at 100 Hz utilizing an opto-electronic motion-capture system (six cameras, MCU240, ProReflex; Qualisys AB, Gothenburg, Sweden). Fourteen reflective hemispheric markers were positioned on seven key anatomical positions on both sides of the body: the glenohumeral joint, lateral condyle of the humerus, dorsum of the wrist, great trochanter, lateral condyle of the femur, and on the boot in positions corresponding to lateral malleolus, and fifth metatarsophalangeal joint. Eight additional markers were positioned on skis and poles; two markers were positioned along each pole, and two markers were positioned on the upper side of the ski, 10 cm from the tip and tail, respectively.

Skiing cycle was defined as beginning with the strike of the right boot and cycle time (CT) was calculated as the time occurring between two successive strikes. Booth strike was identified by the maximum forward displacement of the marker above the boot on metatarsal head [13].

The MW for skiing was estimated based on the changes of the mechanical energies, following the work-energy principle [14]. The position of the body's centre of mass (COM) was calculated using the position and mass of each segment. For the body segments, these data were obtained from the Dempster table [15] while the position of the COM of the poles and skis was determined by the position where a fulcrum maintained the objects in equilibrium. The weight of the boot and of the additional mass required by the protocol were included in the foot mass.

The kinetic ($KE = 0.5\, M\, v^2_{COM}$) and gravitational potential ($PE = M\, g\, h_{COM}$) energy of COM were determined by calculating v_{COM} (the instantaneous velocity of COM in the sagittal plane with respect to a reference system moving at the treadmill belt speed), h_{COM} (the height of COM in the vertical direction with respect to the treadmill belt height) and by knowing M (given by the sum of the body mass of the subject, the mass of the equipment and any additional weight required by the experimental protocol) and g (the gravitational acceleration).

The work necessary to sustain the KE changes (W_{KE}) and the PE changes (W_{PE}) was estimated by calculating, respectively, the sum of positive increments of KE and PE [16]. The total energy of COM (TE) was calculated as the sum of PE and KE. The external MW due to COM motion (W_{EXT}) was determined as the sum of positive increments of TE [14, 17].

The work done to move body segments with respect to body COM (W_{int}) was calculated from the kinetic energy of each segment, KEi, which is obtained from the sum of translational and rotational energy relative to the body COM [17]. Here, it has been assumed that energy transfer can only occur among segments of the same limb. The work required to move body segments, W_{int}, was calculated by accounted separately for W_{int_trunk}, W_{int_arms} and W_{int_legs} as described elsewhere [18] and by summing these contributions. Total MW required to sustain the locomotion, W_{tot} was calculated as the sum of W_{ext}, and W_{int}. All the parameters were calculated over 12 cycles and normalized per unit of meter travelled a body mass and expressed in J m^{-1} kg^{-1}. Kinematic data were processed using Matlab R2020b (MathWorks Inc., Natick, MA, USA) and Excel 2003 (Microsoft Corporation, Redmond, Washington, USA).

Statistical analysis

Kolmogorov–Smirnov normality test was used to assess distributions normality. The effect of added mass was verified for each parameter tested by a one-way ANOVA for repeated measures. When data sphericity was violated, Greenhouse–Geisser correction was applied. When the data resulted statistically significant, a post hoc test was conducted to examine differences between each value and the condition with no weight added. To control for Type I error, the significance level (*p*-value) will be adjusted using a Bonferroni correction by multiplying the *p*-value by the number of pairwise comparisons being made (in this case, three).

Threshold for statistical significance was set to $p<0.05$. Data are all expressed as mean ± SD. The magnitude of the effect of the condition was calculated as partial eta squared (η^2): > 0.01 small, > 0.06 medium, > 0.14 large [19]. Statistical analyses were performed with SPSS statistics (version 22.0, IBM Corporation, Somers, NY).

Results

The speed set for testing the different weight conditions that was selected to correspond to 80% of the maximal speed achieved during the incremental test was 5.4 km·h^{-1} for seven athletes and 5.0 km·h^{-1} for the remaining six athletes.

The BLa, VE, $V'O_2$, and EC were all significantly and largely increased with added weight (Table 1). Post-hoc analysis revealed that for EC, the value increases significantly and by around 2% for every 0.2 kg of mass added on each boot. No effect of the additional masses was found on HR.

No effect of weight was found on CT and W_{KE} (Table 2). The W_{PE} and W_{ext} were found to be significantly and largely dependent by weight with values significantly increasing every added weight. W_{int_trunk}, W_{int_arm} and W_{int_leg} in the condition of zero mass added account for about 3%, 32.5% and 64.5% of the W_{int}. Absolute values of internal work increase

Table 1 Metabolic parameters

	0 kg	0.2 kg	0.4 kg	0.6 kg	F (3.33)	p	η^2
HR (bpm)	174 ± 10	175 ± 11	176 ± 10	178 ± 10	2.1	0.126	0.157
BLa [mmol L^{-1}]	3.07 ± 0.96	3.1 ± 1.03	3.57 ± 1.16	3.56 ± 1.14	4.5	**0.010**	0.289
VE [L min^{-1}]	101 ± 10	105 ± 10	108 ± 12	112 ± 11*	6.6	**0.001**	0.376
$V'O_2$ kg^{-1} [mL min^{-1} kg^{-1}]	54.6 ± 3.2	55.8 ± 2.8	56.7 ± 2.8*	57.5 ± 3.0*	19.2	**0.000**	0.636
EC [J·m^{-1} kg^{-1}]	11.4 ± 0.5	11.7 ± 0.4	11.9 ± 0.4*	12.1 ± 0.4*	23.0	**0.000**	0.676
RPE [CR100]	31 ± 15	30 ± 13	33 ± 14	38 ± 17	2.1	0.120	0.160

Means and standard deviations of the indicated parameters and ANOVA results (* = $p<0.05$ vs. 0 kg condition)

Table 2 Mechanical parameters

	0 kg	0.2 kg	0.4 kg	0.6 kg	F (3.33)	p	η^2
CT [s]	1.12 ± 0.05	1.12 ± 0.05	1.13 ± 0.05	1.11 ± 0.06	0.8	0.478	0.072
W_{PE} [J·m^{-1}·kg^{-1}]	2.48 ± 0.01	2.50 ± 0.01*	2.51 ± 0.01*	2.53 ± 0.01*	182.0	**0.000**	0.943
W_{KE} [J·m^{-1}·kg^{-1}]	0.21 ± 0.05	0.22 ± 0.04	0.20 ± 0.04	0.21 ± 0.05	1.0	0.399	0.085
W_{ext} [J·m^{-1}·kg^{-1}]	2.48 ± 0.01	2.50 ± 0.01*	2.51 ± 0.01*	2.53 ± 0.01*	92.8	**0.000**	0.894
W_{int_trunk} [J·m^{-1}·kg^{-1}]	0.013 ± 0.004	0.014 ± 0.002	0.017 ± 0.004*	0.018 ± 0.004*	8.8	**0.000**	0.446
W_{int_arms} [J·m^{-1}·kg^{-1}]	0.15 ± 0.04	0.15 ± 0.04	0.15 ± 0.05	0.15 ± 0.04	0.06	0.980	0.006
W_{int_legs} [J·m^{-1}·kg^{-1}]	0.29 ± 0.02	0.30 ± 0.02*	0.31 ± 0.02*	0.33 ± 0.03*	16.2	**0.000**	0.595
W_{int} [J·m^{-1}·kg^{-1}]	0.45 ± 0.05	0.46 ± 0.04	0.48 ± 0.05	0.49 ± 0.05*	6.7	**0.001**	0.379
W_{tot} [J·m^{-1}·kg^{-1}]	2.93 ± 0.06	2.96 ± 0.05*	2.99 ± 0.06*	3.02 ± 0.06*	26.2	**0.000**	0.704

Means and standard deviations of the indicated parameters, and ANOVA results (* = $p<0.05$ vs. 0 kg condition) with masses for W_{int_trunk}, W_{int_legs} and W_{int}. The total MW demonstrated a statistically significant and large increase with the additional masses. Post-hoc analysis revealed that for W_{tot}, the value increases significantly and approximately by 1% for every 0.2 kg of mass added to each boot.

Discussion

The results revealed several key findings. Firstly, the addition of a mass of 0.2 kg did not result in any increase in physiological parameters. The addition of masses of 0.4 kg or more, on the other hand, has caused significant differences in oxygen uptake and metabolic cost. Instead, the addition of extra weight, starting from just 0.2 kg, resulted in an increase in both the MW done to lift the body and the skiing equipment against gravity, as well as the work needed to move the segments of the body with respect to body COM.

In contrast to other studies where the effect of weight has been investigated solely by evaluating its impact on some physiological variables, in this investigation, we have introduced the estimation of the different components that contribute to the total MW. Furthermore, to enhance the validity of our findings, we specifically recruited athletes who participate in official ski mountaineering competitions with race equipment and designed the protocol to replicate effort levels that are comparable to those encountered in a vertical race [4].

The metabolic parameters collected in the present investigation showed that the cost of locomotion in ski mountaineering significantly increased with increasing added load at boot level. The rate of increase can be estimated to be 2.1% for every 0.2 kg of mass added to each side. This aligns with a study in cross-country skiing, where the addition of 0.25, 0.50, and 0.75 kg to each roller ski resulted in an increase in metabolic rate by approximately + 2–3% for each 0.2 kg when skating on uphill terrain [20].

In previous studies on ski mountaineering, smaller increases in EC compared to ours have been found. In these studies, a relationship between added weight and EC has been identified. Extrapolating this proportionally to a 0.2 kg weight change, a 0.94% [8] and 1.3% [7] change in EC can be estimated.

It is important to note that the mentioned studies on ski mountaineering involved larger mass changes ranging from 0.5 to 2.15 kg per side and that the skiing speed and/or slope were lower, resulting in correspondingly lower skiers effort and metabolic rates. This factor, along with extrapolating results for weights lower than those tested, may explain the differences and confirming the importance of measuring the effect of equipment weight in scenario as close as possible to real competitive conditions.

In our results neither heart rate nor the perceived exertion showed a statistically significant effect of weight. Regarding heart rate, although there was a tendency for it to increase by 1 or 2 bpm for every 0.2 kg in weight, this did not result in any significant effect in the statistical test. This lack of significance may be attributed to the presence of a confounding factor, which adds another source of variability between trials beyond what was tested. One potential confounder could be an increase in heart rate over the entire duration of the exercise. However, it is important to emphasize that this aspect potentially affecting heart rate is minor on the other investigated physiological variables [21] and, due to the randomized design, it has not introduced bias into the study results. Similarly, an increase in the rate of perceived exertion may have occurred throughout the session, and the subjects' limited familiarity with the Borg scale may have contributed to not accurately evaluating variations in perception in response to very small changes in external loads.

In previous experiments, due to the significant changes in weight and/or complete equipment replacements, the subjects were not blinded. This most likely influenced the subjects' responses and perceptions, potentially introducing bias, as observed in other sports [9]. Since weights were added blindly in our investigation, we are confident that there was no effect resulting from the subjects' conditioning.

As far as MW is concerned, we found that due to the added weight, the internal work, which refers to the displacement of segments relative to the COM, underwent a significantly greater percentage increase compared to the external work (+ 2.88% and + 0.68% every 0.2 kg of mass added respectively). However, considering that at the slopes adopted in this study, internal MW constitutes only 15% of the total MW, with the remaining 85% attributed to external MW, it can be concluded that the increased work found in the present investigation can be primarily attributable to the need to lift the additional weight. It can be speculated that, at less steep slopes, the increase in weight would lead to a greater rise in internal work rather than external work. Indeed, at low slopes, less work is required against gravity leading to a decrease in the effect of added weight on total work. On the contrary, the internal work has been previously observed to remain constant with varying slopes [22].

The results of the present study did not show any variation in the skiing cadence with changes in boot weight. This leads us to conclude that the observed variation in internal work is not influenced by cadence changes [23] but only by the increased distal load. Furthermore, the absence of cadence variations suggests that the skiers did not react to an increase in distal mass by reducing cadence to reduce internal work. This behaviour is in contrast with theories that consider the leg as a simple pendulum during swing phase of locomotion, the natural frequency of which is dependent upon its inertial characteristics. Considering this, the greater moment of inertia given by larger load on foot would result in a lower natural frequency [24]. On the contrary, it would be also reasonably to expect that heavier load positioned on the foot would be more difficult to swing forward, leading subjects to potentially shorten their steps and consequently increase their cadence. An unchanged step cadence, as found in our results, or a slightly increased step length in face of an increased distal load have been already observed for other locomotion modes, too. In cross country skiing, the addition of distal load did not lead to any changes in cycle timing [20]. In running it has been demonstrated that lower limb movements were largely unaffected by load as large as 0.5 kg added to each tight or foot [10, 25]. Changes in step length were observed in walking only when larger masses are used. Increases of 1% and 5% were found with an added mass of 2 kg [26] and 4 kg, respectively [27]. It appears, therefore, that unless a significantly higher external load is imposed, while maintaining a constant locomotion velocity, the cadence remains unchanged instead of adapting to achieve an energetically optimal state based on the pendular dynamic of the swing [24]. This fit the preferred movement path paradigm that suggests that the kinematic patterns of highly automatized movements remain unchanged when adapting to equipment modifications [28].

We calculated a 2.1% increase in the metabolic cost of skiing for every 0.2 kg of mass added to each foot, while the estimated total MW showed an increase of 1.0%. Our results indicate then that the metabolic cost of locomotion increases at a higher rate compared to the estimated total MW. These findings suggest that the added weight not only increases the muscle work required for mechanical tasks, but it also likely leads to an increase in isometric contractions and co-contractions. These contractions consume energy without producing a corresponding net MW output. The discrepancy between the increase in metabolic and MW could also be attributed to additional muscle work for negative MW, such as decelerating the forward swing of the leg. This aspect was not included in the workload estimation because the employed method does not account for the decrease in mechanical energy [17].

In contrast to previous investigations, we have specifically designed our protocol to closely mimic the physical demands of ski mountaineering competitions. Previous investigation assessing the effect of changing equipment's mass was run at a speed in the range of 3.3–4.5 km/h, intended to simulate recreational ski touring [7, 8] The speed tested in the present investigation fell within the range of that of a vertical race simulation [29]. Similarly, previous investigation testing equipment weight have been conducted at intensity of 72% of VO_{2max}. The physiological effort of present investigation, being on average 82% of the maximal aerobic capacity of the subject was comparable to those of a real [4] and simulated [29] vertical race. A further choice aimed at obtaining information more valid for competitions was to recruit competitive skiers in contrast to other investigations including participant skilled and experienced in ski touring [7, 8].

Our current investigation confirms that a decline in skiing economy occurs even with small weight variations, which are within a potential weight difference between different models of competitive equipment. We focused our investigation on understanding the effect of weight on skiing at a constant velocity and slope. Subsequent investigations should aim to confirm whether lighter boots continue to have a positive impact on a real scenario implying variations in slope and in speed. Furthermore, it should be evaluated if lighter boots may enhance agility and enable skiers to better face changes in slope, obstacles, or snow conditions. Ski boot manufacturers should prioritize lightweight designs, particularly for race formats like vertical races, where minimizing skiers' effort during climbing sections is crucial, while for race formats including also downhill sections, safety should be considered at first. Here, we hypothesized that an increase in boot weight has a detrimental effect on uphill performance. Investigating whether appropriate modifications to the boot that result in an increase in its weight could be advantageous for downhill performance was beyond the aim of our study. It should be noted, however, that in races involving both uphill and downhill sections, such as individual races, the time spent on uphill sections is typically eight times greater than that spent on downhill sections [2]. Therefore, improvements in downhill performance allowed by heavier equipment would need to be substantial to offset the deterioration in performance during the long-lasting uphill sections. The trade-off between worsening the uphill phase and improving the downhill phase should be assessed. Manufacturers and skiers should explore developing and utilizing distinct boot models tailored for specific ski mountaineering disciplines, taking into account the impact of both uphill and downhill sections on the final result.

Limitations

MW cannot directly be measured in locomotion task and specifically in ski mountaineering. However, it can be estimated through different calculation methods. The method used in present investigation, based on the calculation of the energy changes, rely on the knowledge of the body segments and of the COM motion and is considered a valid approach for comprehensive understanding of the mechanics of terrestrial locomotion [17]. Comparative investigations have demonstrated that the method adopted here provide a good approximation of the body COM displacement and of external MW for walking, running and skipping gait when compared to the use of force platforms [30]. Methods for estimating power at each joint could potentially provide a better understanding, however, they would require measurements of ground reaction forces during skiing, which are not straightforward in ski mountaineering.

Despite keeping the number of trials relatively low, preceding the first trial by a warm up period of similar intensity and duration of the trials and incorporating a 5-min rest period, ensuring exercise intensity was below the second threshold, an increase in heart rate and rate of perceived exertion throughout the testing session may have occurred. In our design, randomization of the trials has eliminated the order effect but may have increased the variability of the measurements, which could have obscured the significance of the effect of adding weights. Future studies should better control for this source of variability factor by including longer rest periods, ensuring better hydration, and monitoring the participants' recovery more thoroughly before subsequent trials. In this study, only male athletes were involved, and the transferability of the results to female athletes may be limited. Future studies should assess the effect of weight variation in equipment on women.

Another potential limitation is that the additional weight has been placed under the sole of the boot, in a position which could therefore be lower than the centre of gravity. This weight distribution is as it would be in boots designed for greater solidity and safety during the descent phase.

Participants reported that they found the friction of the skis to be generally greater on the treadmill rather than on snow. Accordingly, when interpreting the present results, it is important to consider that the observed effects may differ under real outdoor scenarios. Nevertheless, conducting the study on a treadmill was necessary to eliminate all the potential confounding effect of speed variations and to investigate the metabolic and biomechanical parameters.

Conclusion

The results confirmed our hypothesis, the findings of the present investigation indicate a negative impact of extra weight on ski mountaineering economy that extends below the range of weight suggested by previous studies and applies to small mass variations that are more representative of actual weight fluctuations experienced with competitive equipment. As expected, the increase in the MW was high in the component devoted to leg movement. From a practical point of view the present investigation shows that even small changes toward lighter equipment may lead to changes in EC with expected improvement in endurance performance [31]. According to our investigation, to reduce the MW and then the metabolic cost, ski mountaineers should prefer to wear lightweight boots especially for those races where the climbing portions is relevant.

Acknowledgements We gratefully acknowledge the financial support provided by the CARITRO Foundation through the grant "Ricerca e Sviluppo 2019" under project number ID 10402, cod. SIME 2019.0193.2019. We extend our heartfelt gratitude to the athletes who generously volunteered to participate in this scientific research test.

Author contributions All authors contributed to the study's conception and design. Material preparation, data collection, and data analyses were performed by LB, SN, LG, MD, and BP. Data interpretation, manuscript writing, and revision for important intellectual content were performed by LB, AS, AF, CZ, FS, and BP. All authors read and approved the final manuscript.

Funding Open access funding provided by Università degli Studi di Verona within the CRUI-CARE Agreement.

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Bortolan L, Savoldelli A, Pellegrini B, Modena R, Sacchi M, Holmberg HC et al (2021) Ski mountaineering: perspectives on a novel sport to be introduced at the 2026 Winter Olympic games. Front Physiol 12:737249. https://doi.org/10.3389/fphys.2021.737249
2. Duc S, Cassirame J, Durand F (2011) Physiology of ski mountaineering racing. Int J Sports Med 32:856–863. https://doi.org/10.1055/s-0031-1279721
3. Schenk K, Faulhaber M, Gatterer H, Burtscher M, Ferrari M (2011) Ski mountaineering competition: fit for it? Clin J Sport Med 21:114–118. https://doi.org/10.1097/JSM.0b013e31820f903e
4. Fornasiero A, Savoldelli A, Boccia G, Zignoli A, Bortolan L, Schena F et al (2018) Physiological factors associated with ski-mountaineering vertical race performance. Sport Sci Health 14:97–104. https://doi.org/10.1007/s11332-017-0407-0
5. Bortolan L, Pellegrini B, Verdel N, Holmberg H-C, Supej M (2023) Development of equipment for ski mountaineering, a new Olympic event. Appl Sci 13:5339
6. ISMF (2022) International Ski, Mountaineering Federation, Sporting Rules & Regulations 22–23. http://www.ismf-ski.org. Accessed 6 Feb 2023
7. Skinner ADC, Koehn D, Buchanan CA, Dalleck LC (2019) Effect of equipment weight on energy cost and efficiency during simulated uphill ski touring. Int J Res Exerc Physiol 73–86. https://ijrep.org/effect-of-equipment-weight-on-energy-cost-and-efficiency-during-simulated-uphill-ski-touring/

8. Tosi P, Leonardi A, Schena F (2009) The energy cost of ski mountaineering: effects of speed and ankle loading. J Sports Med Phys Fitness 49:25–29. https://doi.org/10.3389/fspor.2022.844883
9. Mohr M, Trudeau MB, Nigg SR, Nigg BM (2016) Increased athletic performance in lighter basketball shoes: shoe or psychology effect? Int J Sports Physiol Perform 11(1):74–9. https://doi.org/10.1123/ijspp.2014-0538
10. Martin PE (1985) Mechanical and physiological responses to lower extremity loading during running. Med Sci Sports Exerc 17(4):427–33. https://doi.org/10.1249/00005768-198508000-00004
11. Myers MJ, Steudel K (1985) Effect of limb mass and its distribution on the energetic cost of running. J Exp Biol 116:363–73. https://doi.org/10.1242/jeb.116.1.363
12. Péronnet F, Massicotte D (1991) Table of nonprotein respiratory quotient: an update. Can J Sport Sci 16:23–29
13. Zeni JA, Richards JG, Higginson JS (2008) Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait Posture 27(4):710–4. https://doi.org/10.1016/j.gaitpost.2007.07.007
14. Cavagna GA, Kaneko M (1977) Mechanical work and efficiency in level walking and running. J Physiol 268(2):467–481. https://doi.org/10.1113/jphysiol.1977.sp011866
15. Dempster WT, Gaughran GRL (1967) Properties of body segments based on size and weight. Am J Anat 120(1):33–54. https://doi.org/10.1002/aja.1001200104
16. Zatsiorsky VM (2000) Mechanical work and energy in human movement. In: Kinetics of human motion. Human Kinetics, Leeds
17. Willems PA, Cavagna GA, Heglund NC (1995) External, internal and total work in human locomotion. J Exp Biol 198(Pt 2):379–93. https://doi.org/10.1242/jeb.198.2.379
18. Pellegrini B, Peyré-Tartaruga LA, Zoppirolli C, Bortolan L, Savoldelli A, Minetti AE et al (2017) Mechanical energy patterns in nordic walking: comparisons with conventional walking. Gait Posture 51:234–238. https://doi.org/10.1016/j.gaitpost.2016.10.010
19. Richardson JTE (2011) Eta squared and partial eta squared as measures of effect size in educational research. Educ Res Rev 6(2):135–147. https://doi.org/10.1016/j.edurev.2010.12.001
20. Bolger CM, Bessone V, Federolf P, Ettema G, Sandbakk Ø (2018) The influence of increased distal loading on metabolic cost, efficiency, and kinematics of roller ski skating. PLoS One 13(5):e0197592. https://doi.org/10.1371/journal.pone.0197592
21. Zuccarelli L, Porcelli S, Rasica L, Marzorati M, Grassi B (2018) Comparison between slow components of HR and VO_2 kinetics: functional significance. Med Sci Sports Exerc 50(8):1649–1657. https://doi.org/10.1249/MSS.0000000000001612
22. Saibene F, Minetti AE (2003) Biomechanical and physiological aspects of legged locomotion in humans. Eur J Appl Physiol 88(4–5):297–316. https://doi.org/10.1007/s00421-002-0654-9
23. Minetti AE, Capelli C, Zamparo P, Prampero PED, Saibene F (1995) Effects of stride frequency on mechanical power and energy expenditure of walking. Med Sci Sports Exerc 27(8):1194–202. https://doi.org/10.1249/00005768-199508000-00014
24. Stegemann J (1983) Exercise physiology: physiological bases of work and sport. George Thieme, Verlag Stuttgart, New York
25. Cavanagh PR, Kram R (1989) Stride length in distance running:velocity, body dimensions, and added mass effects. Med. Sci. Sports Exerc 21(4):467–79
26. Royer TD, Martin PE (2005) Manipulations of leg mass and moment of inertia: effects on energy cost of walking. Med Sci Sports Exerc 37(4):649–56. https://doi.org/10.1249/01.MSS.0000159007.56083.96
27. Browning RC, Modica JR, Kram R, Goswami A (2007) The effects of adding mass to the legs on the energetics and biomechanics of walking. Med Sci Sports Exerc 39(3):515–25. https://doi.org/10.1249/mss.0b013e31802b3562
28. Nigg BM, Vienneau J, Smith AC, Trudeau MB, Mohr M, Nigg SR (2017) The preferred movement path paradigm: influence of running shoes on joint movement. Med Sci Sports Exerc 49(8):1641–1648. https://doi.org/10.1249/MSS.0000000000001260
29. Lasshofer M, Seifert J, Wörndle A-M, Stöggl T (2021) Responses and predictors of performance in a simulated competitive ski mountaineering race. J Sport Sci Med 20:250–257. https://doi.org/10.52082/jssm.2021.250
30. Pavei G, Seminati E, Cazzola D, Minetti AE (2017) On the estimation accuracy of the 3D body center of mass trajectory during human locomotion: inverse vs. forward dynamics. Front Physiol 8:129. https://doi.org/10.3389/fphys.2017.00129
31. Bassett DR, Howley ET (2000) Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 32(1):70–84. https://doi.org/10.1097/00005768-200001000-00012