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Original Research Article

Effect of Equipment Weight on Energy Cost and Efficiency during Simulated Uphill Ski Touring

Adam D.C. Skinner[1], Duncan Koehn[1], Christina A. Buchanan[1], Lance C. Dalleck[1]

[1]High Altitude Exercise Physiology Program, Western Colorado University, Gunnison, CO, USA

ABSTRACT

Purpose The purpose of this study was to quantify changes in energy cost (EC) associated with increased ski touring equipment weight during simulated uphill ski touring at a constant speed and grade and to identify potential factors affecting energy cost other than equipment weight. ***Methods*** 8 subjects skinned on a treadmill at a constant speed and grade using three different ski touring setups (6.1, 7.9 and 10.4kg in total mass) in a randomized order. Heart rate, respiratory exchange ratio, blood lactate concentration and energy expenditure were measured while subjects maintained a steady state workload. ***Results*** A statistically significant positive correlation was found between total weight (setup mass + participant mass) and energy cost (r = 0.501, n = 24, p < 0.05). Non-linear increases were found in EC (13.8, 14.7, 16.3 J kg^{-1}m^{-1}), heart rate (164, 167, 177 bpm) and oxygen consumption (41.8, 44.3, 49.1 mL kg^{-1}min^{-1}) with 6.1, 7.9 and 10.4kg setups respectively. ***Conclusions*** A significant relationship exists between equipment weight and measured energy cost of uphill skinning, but a greater increase in workload was observed between the 7.9kg and 10.4kg setups compared to the changes found between the 6.1kg and 7.9kg setups. This may be due to the binding design on the heaviest setup, which was different from the bindings on the two lighter setups. When choosing an equipment setup, recreational ski mountaineers should consider the type of binding used and its potentially greater effect on energy cost compared to equipment weight alone.

KEY WORDS: Exercise Physiology, Ski Touring.

Introduction

Ski touring has become a popular winter leisure activity in mountainous regions all over the world. Ski touring requires the use of boots with ankle rotation capabilities, heel-release bindings and adhesive skins applied to the bottom of skis to ascend and ski down terrain not accessible by chairlift. Equipment for ski touring has evolved substantially in recent years to be lighter and increase locomotion efficiency for the user[1]. Advances in boot and binding design as well

as climbing techniques in uphill skiing have led to increases in energy efficiency and performance[2-4]. While saving weight may seem like an effective way to abate energy cost, skiers and manufacturers claim that heavier equipment (skis, boots, bindings) may actually be preferable during the demanding descents of backcountry ski touring due to their associated performance characteristics[4].

Though these studies illustrate there are many factors that affect locomotion efficiency, only one examined the potential effects of equipment weight on energy cost and efficiency during ski touring[1]. During this study weights ranging from 0.5kg to 2 kg were attached to participants' ankles during repeated uphill ski mountaineering bouts on snow at a self-selected pace. Researchers found that locomotion efficiency in ski mountaineering changed only slightly with ankle loading; a 1kg weight added to the ankles of an 80kg skier (including gear) yielded an energy cost increase of 3 percent. They determined that these changes with ankle loading appear to be slight in recreational skiers, but that this energy cost increase would be accentuated in elite athletes due to their level of energy expenditure and time spent at high exercise intensities during competition[5-7]. While the study by Tosi et al.[1] was the first and only to examine the effects of loaded weight on efficiency of ski touring, some aspects of their study could be refined to control for factors that play a role in energy cost providing the opportunity to better understand exactly how the weight of a skier's equipment affects energy cost and locomotion efficiency.

The aim of the current study was first to add to the relatively sparse literature relating to the energy kinematics on ski touring/mountaineering. Researchers also aimed to determine whether or not equipment weight alone affects energy cost of ski touring and therefore has an impact on locomotion efficiency. Additionally, it addressed whether or not heavier equipment, that may be ideal for descending, would significantly increase energy cost during uphill locomotion. Finally, researchers aimed to quantify the changes in energy cost and efficiency while climbing with ski touring setups of different weights. The purpose of this study was to quantify the effect of ski touring equipment weight on the energy cost of simulated uphill skiing on a treadmill in male recreational backcountry skiers. We hypothesized that energy cost of uphill locomotion would increase proportionately with the added weight of the ski equipment used; that is, utilizing one touring setup that weighs more than another would yield a proportionately higher energy cost and therefore decrease locomotion efficiency.

Methods

Subjects
Eight healthy males, skilled and experienced in ski touring and acclimatized to moderate elevation (2250m-2750m) took part in this study. All procedures were completed in the

High Altitude Performance Laboratory (HAPLab) on the Western State Colorado University campus (2250m elevation). All participants took part voluntarily, giving informed consent prior to participating in the study. Researchers gained approval to conduct this study through the Western State Colorado University Human Research Committee. Mean baseline measurements of participants appear in Table 1.

Table 1. Descriptive characteristics of the eight participants (mean ± SD).

Age (years)	Height (cm)	Body mass (kg)	Maximal Heart Rate (beats min^{-1})	VO$_2$max (mL·kg^{-1}·min^{-1})
24.0 ± 3.7	181.5 ± 6.2	75.7 ± 6.7	190.0 ± 9.2	62.3 ± 11.1

Experimental Design

Participants made two visits to the HAPLab during this repeated measures study. During the first session participants completed an informed consent as well as a physical activity readiness questionnaire and a health history questionnaire. Participants were then familiarized with uphill skiing on the treadmill during a low-intensity 5-minute familiarization session and performed a baseline test measuring maximal oxygen consumption (VO$_2$max). The familiarization session acted as a warm up for the subsequent graded exercise test. During the second session participants performed three submaximal bouts using three different skiing setups in a randomized fashion. Figure 1 illustrates the design of this study.
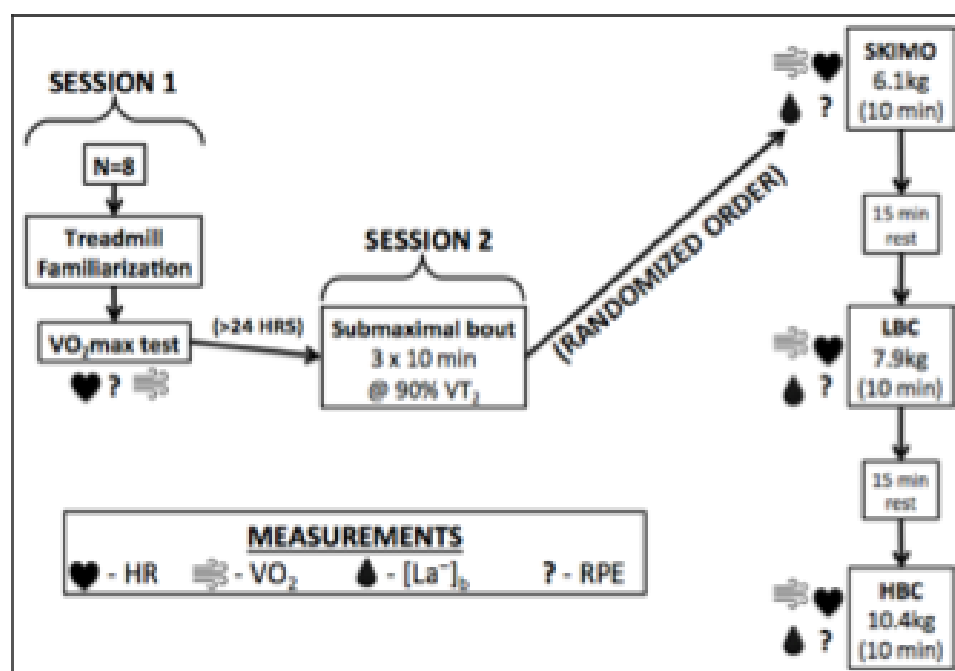

Figure 1. Experimental flow chart of the present study; VO2 - oxygen consumption, [La⁻]b – blood lactate concentration; RPE – rating of perceived exertion; HR – heart rate.

Procedures

Equipment Setups

Three different ski setups were utilized during this study. Setup 1 (SKIMO) represented a ski mountaineering setup and consisted of a lightweight ski (Tour Rando 178cm, SKI TRAB, Bormio, IT), tech bindings (TLT ST Demo, DYNAFIT, CO, USA) and lightweight boots (Alien, SCARPA, CO, USA). Setup 2 (LBC) represented a lightweight backcountry skiing setup and consisted of a lightweight alpine ski (106 carbon 175cm, ROMP Skis, CO, USA), tech bindings (TLT ST Demo, DYNAFIT, CO, USA), and a mid-weight alpine touring boots (Mercury, DYNAFIT, CO,

USA). Setup 3 (HBC) was a heavy backcountry setup with a heavy alpine ski (106 175cm, ROMP Skis, CO, USA) a frame alpine touring binding (Tracker MNC 16 L, Atomic, AT), and the same mid-weight alpine touring boot from the LBC setup (Mercury, DYNAFIT, CO, USA). Figure 2 illustrates the differences in design between the two binding types used in this study. All setups included a pair of climbing skins (Ascension STS, Black Diamond, UT, USA) cut specifically for that ski to control for friction between the ski and treadmill. Measured mass of the three setups, including skins, is displayed in Table 2.

Table 2. Inter-setup mass comparisons (kg, equipment reported as a pair).

Setup	Skis, bindings, skins	Boots	Total	% change from SKIMO	Total mass (mean ± SD)	% Total mass change from SKIMO
SKIMO	4.4	1.7	6.1	--	81.5 ± 6.1	--
LBC	4.8	3.1	7.9	+ 29.5%	83.3 ± 6.1	+ 2.2% ± 0.1
HBC	7.3	3.1	10.4	+ 70.5%	85.8 ± 6.1	+ 5.3% ± 0.4

Boots were provided in sizes 27 and 29 (mondopoint). Participants were fit with boots prior to the familiarization session.

Boot and binding adjustments were made by a certified ski repair technician. Setup mass was measured using a digital scale.
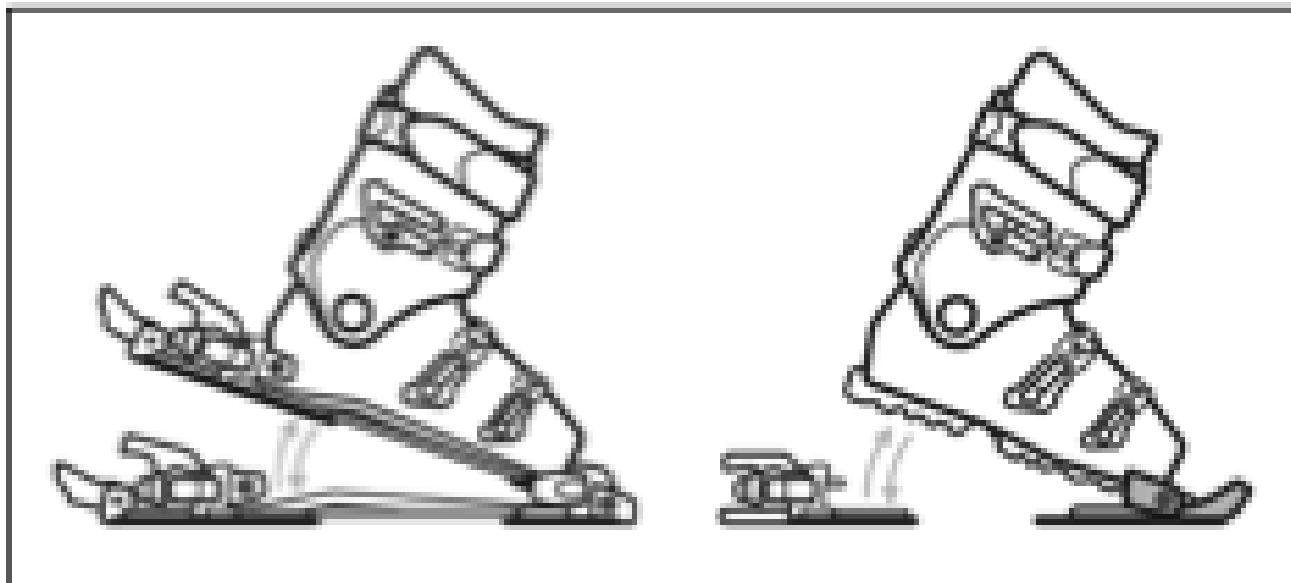
Figure 2. Frame bindings (A) vs. tech bindings (B). Note that the frame binding remains attached to the boot during a stride while the tech binding remains attached to the ski and the boot is able to rotate independently.

Participants then underwent a familiarization session on the motorized treadmill (Fitnex Fitness Equipment, Inc., TX, USA). The familiarization session consisted of three portions: (1) researchers explaining equipment fit, use, and treadmill procedures to participants, (2) slow (less than $1m \cdot s^{-1}$), low grade (less than 10%) uphill locomotion on treadmill using skis while being spotted at the lower back by researchers, and (3) a self-selected pace locomotion at a steeper grade (15%) on the treadmill for two minutes. Participants were instructed by researchers to select a speed that was comfortable and that they could sustain for the duration of a typical (non-competitive) ski tour. Participants participated in each portion of the familiarization until they demonstrated proficiency and gave verbal affirmation that they felt comfortable with uphill skiing on the treadmill. Researchers determined that

if a subject could not demonstrate proficiency skiing on the treadmill they would be removed from the study as a safety precaution. No participants were removed from the study. Participants took part in the familiarization session while wearing the SKIMO setup prior to their VO$_2$max test.

Maximal Graded Exercise Test
Following the familiarization session, participants participated in a maximal graded exercise test using ski touring equipment on a treadmill to measure VO$_2$max. During maximal test boots and bindings were in walk mode to allow for full range of uphill striding motion and participants used the 7-degree heel risers on the provided bindings. The test began at 15% grade with the self- selected speed determined during the familiarization session. Treadmill grade was increased 3%

per minute until volitional fatigue. Average total test time was 10.1 ± 1.3 minutes (mean ± SD). Oxygen consumption (VO_2), carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) were measured using a gas analyzer (True One 2400, Parvomedics, Sandy, UT, USA). Heart rate and rating of perceived exertion (RPE) measurements were taken at the end of every one-minute stage during the test. Each subject was given verbal encouragement to provide a maximal effort during this test. Researchers determined that VO_2max was attained by verifying that each subject attained an RER of at least 1.0 and a change in VO_2 less than 350 mL·min^{-1} between 15-second sampling periods was observed. Following the conclusion of the test, participants performed a 5-minute cool-down session at low intensity. Researchers monitored participants' heart rate during this cool-down period to ensure proper recovery.

Submaximal Exercise Protocol

Participants returned to the HAPLab for their second and final visit between 1 day and 1 week after their initial visit. Resting measurements (height, body mass, resting HR, blood lactate) were taken before the submaximal tests. To determine differences in EC of using ski touring setups of differing weight all participants performed three separate submaximal treadmill bouts—one while using each ski setup (SKIMO, LBC, HBC). The order in which participants used the three setups was randomized by a computer program. During the sub-maximal test, boots and bindings were in walk mode

to allow for full range of uphill striding motion and participants used the 7-degree heel risers on the provided bindings. Researchers calculated participants' second ventilatory thresholds (VT_2) using VE and VCO_2 measurements obtained during their maximal exercise test. Based upon these calculations, the submaximal exercise test protocol was developed to keep participants below VT_2 while achieving a steady state of exercise long enough to collect data measurements. During this test the treadmill was set to the speed and grade corresponding to the 90% of the participants HR at VT_2 as determined from their maximal exercise test. This intensity was reported to be less than that of a competitive ski mountaineer[6] during a race, and was intended to simulate a bout of recreational ski touring[5,7]. Speed and grade means for submaximal tests were 1.05±0.07 m/s and 25.12±5.1% grade respectively (mean ± SD). Each submaximal bout lasted ten minutes, which pilot trials and previous studies demonstrated was long enough to reach a steady state of exercise[2,4]. Gas exchange was collected on a breath-by-breath basis and averaged in 15-s intervals for analysis. Expired gasses were collected and measured during all ten minutes of each submaximal bout. HR and RPE were measured once during each minute of the test. To ensure data reflected workload parameters at a steady state of exercise, only HR, VO_2, and RER measurements taken from the final five minutes of each test were considered. These measurements were subsequently averaged and reported as mean measurements for the

corresponding touring setup. Three blood lactate measurements were taken via finger prick during the eight, ninth, and tenth minutes of each test (Lactate PLUS, NOVA Biomedical, MA, USA). Each submaximal bout was separated by a 15-minute rest period during which participants rested passively and researchers were able to change equipment in preparation for the subsequent test.

Calculating Energy Cost

EC ($J \cdot kg^{-1} \cdot m^{-1}$) was calculated by the value of oxygen consumption (VO_2) (assuming an energy equivalent of 20.9 kJ per liter O_2) per mass unit (body mass plus equipment) divided by the speed[1-3]. This calculation allowed for comparison of energy expenditure relative to the body mass, loaded weight and speed during individual bouts. Two previous studies examining optimal slopes and speeds in uphill ski mountaineering calculated EC in terms of relative vertical displacement[2-3]. However, recent studies in which researchers quantified EC of ski mountaineering have reported EC in terms of meters traveled, not including vertical displacement[1-3]. Therefore, EC in this study was calculated and reported for linear meters traveled using the following equation: EC ($J \cdot kg^{-1} \cdot m^{-1}$) = 20.9*$VO_2$ ($J \cdot kg^{-1} \cdot min^{-1}$)/V($m*min^{-1}$)

Statistical Analysis

Descriptive statistics were used to determine the mean, SD, and mean percent change for each of the baseline tests and anthropometric measurements. Data was checked for normal distribution using the Kolmogorov-Smirnov test for normality. A Pearson's r correlation was conducted to measure the relationship between total weight and energy cost. A one-way analysis of variance (ANOVA) was employed to determine the effects of the independent variable (ski setup weight) on multiple dependent variables (EC, % VO_2, [La$^-$]b, HR). Alpha level was set at $p<0.05$ to determine statistical significance and all confidence intervals (CI) were set to 95%. After main effect significance was found, a Bonferroni test was used for post hoc comparisons. IBM SPSS 24 statistical software (Armonk, NY) was utilized for all data analysis.

Results

One participant did not complete the study due to scheduling conflicts. Data for eight participants who completed the study are presented. Submaximal tests were ten minutes in length. Three [La$^-$]b measurements were taken during minutes 8, 9, and 10 of each test and were averaged for data analysis. HR, RER, and VO_2 values were averaged for the final five minutes of each test and these average values were used to identify changes between the three setups. Figure 3 illustrates the steady state VO_2 and HR achieved during a typical submaximal session on the treadmill. Though researchers had no defined criteria for determining whether participants reached a steady state of exercise, previous studies have demonstrated that 10 minutes is sufficient in bringing athletes to a steady state at an intensity below VT_2 [2-4].
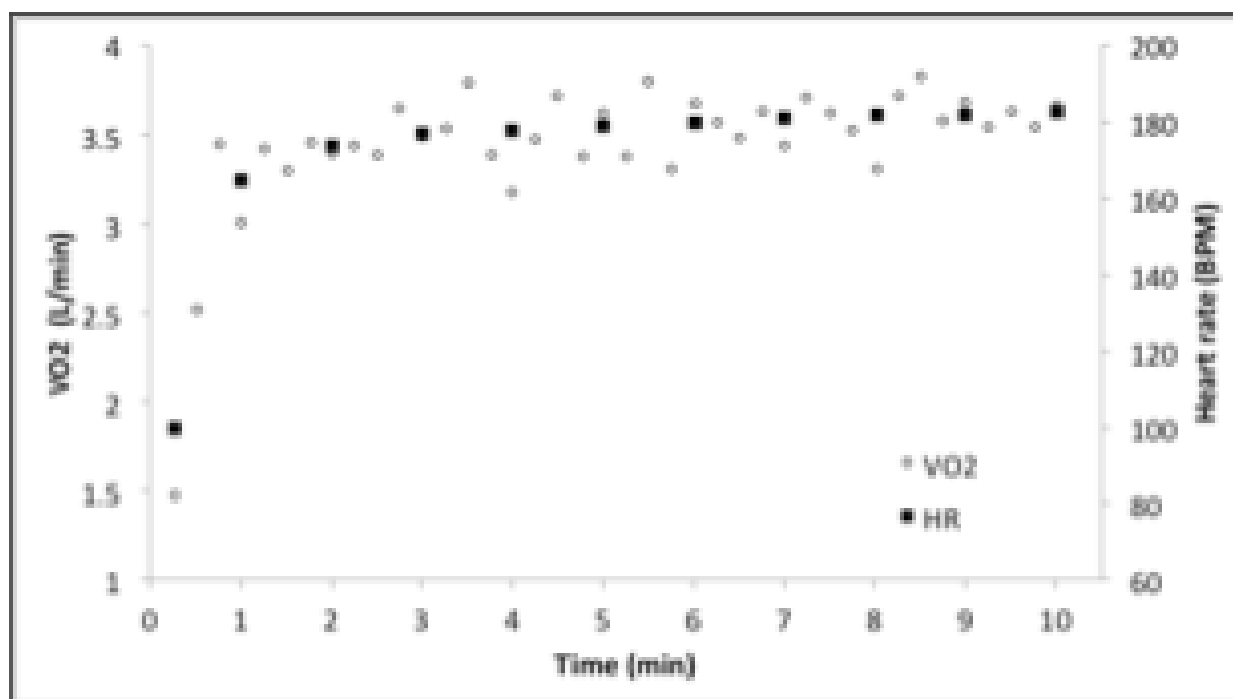
Figure 3. VO_2 and HR data for a typical submaximal test. Data for EC calculations and analysis were obtained and averaged in steady state conditions from 5 to 10 min.

Physiological responses as well as energy cost of simulated uphill ski touring using the three provided setups are displayed in Table 3. Percent of maximal oxygen consumption (% VO_2max) and percent of maximal heart rate (% HR_{max}) were calculated by dividing average VO_2 and HR values during their respective submaximal test by VO_2max and HR_{max} attained during the maximal graded exercise test.

Table 3. Average results for submaximal trials using the three different equipment setups (mean ± SD).

	EC $(J \cdot kg^{-1} \cdot min^{-1})$	VO_2 $(mL \cdot kg^{-1} \cdot min^{-1})$	% VO_2max	$[La^-]b$ (mmol)	RER	HR (bpm)	% HR_{max}
SKIMO	13.8±1.8	41.8±8.2	67.0±4.1	2.1±0.6	0.83±0.02	164 ± 5.9	86.4 ± 3.3
LBC	14.7±2.3	44.3±9.5	70.9±5.5	2.8±1.0	0.85±0.02	167 ± 7.2	87.9 ± 5.2
HBC	16.3±2.4	49.1±9.8	78.9±5.5	3.3±1.0	0.88±0.02	177 ± 7.4	93.3 ± 3.7
	#+&	#+&	#+&	&	&	+&	+&

EC - energy cost; VO_2 - oxygen consumption; % $VO_{2\,MAX}$ – percent maximum oxygen consumption; $[La^-]_b$ – blood lactate concentration; RER – respiratory exchange ratio; HR – heart rate; %HR_{MAX} – percent maximal heart rate. Statistically significant (p < 0.05) differences in measurements between setups are signified by the following: SKIMO-LBC (#), LBC-HBC (+), SKIMO-HBC (&)

Pearson correlation coefficient was calculated for the relationship between total weight (body mass + setup weight) and energy cost. A statistically significant positive correlation was found [r = 0.501, n = 24, p < 0.05]. The coefficient of determination (r^2 = 0.251) indicated a small relationship between the two variables, i.e. greater total weights were associated with greater energy costs of locomotion.

Energy cost and % VO$_2$max

Energy cost and % VO$_2$max both increased with each incremental increase in equipment setup weight. There was a significant effect of ski setup on EC [F = 30.97, p = 0.001]. Post hoc testing revealed significant differences (p<0.05) in EC between the SKIMO setup and both the LBC [0.82, CI (0.51, 1.58)] and HBC setups [2.43, CI (1.38, 3.47)], as well as a significant difference between the LBC and HBC setups [1.61, CI (1.00, 2.23)]. Figure 4a illustrates differences in mean EC between the three equipment setups. There was a significant effect of setup on % VO$_2$max [F = 28.23, p = 0.001] and post hoc tests showed similar significant differences (p<0.05) between the three setups [SKIMO vs LBC: 3.9, CI (0.50, 7.20); SKIMO vs HBC: 11.9, CI (7.00, 16.80); LBC vs HBC: 8.0, CI (4.70, 11.30)]. These data suggest that there are greater increases in both EC and % VO$_2$max between the LBC and HBC setups than between the SKIMO and LBC setups. Figure 4b shows the increase in % VO$_2$max between the SKIMO, LBC, and HBC setups.

Blood lactate and RER

There was a significant effect of setup on both [La$^-$]b and RER [F = 7.20, p = 0.025; F = 6.74, p = 0.029, respectively]. Post hoc tests revealed a significant difference (p<0.05) in [La$^-$]b between the SKIMO and HBC setups [1.19, CI (0.262, 2.125)] but no significant difference between the SKIMO and LBC or between the LBC and HBC setups (p>0.05). Similar findings existed for RER, with significant differences (p<0.05) between the SKIMO and HBC setups [0.04, CI (0.009, 0.08)] and no significant difference between the SKIMO/LBC or LBC/HBC setups (p>0.05).

Heart rate and % HR$_{max}$

There was a significant effect of setup on HR and % HR$_{max}$ [F = 23.31, p = 0.001; F = 23.65, p = 0.001, respectively]. For changes in HR, post hoc tests revealed statistically significant (p<0.05) differences between the SKIMO and HBC [13.1, CI (7.40, 18.86)] and the LBC and HBC [10.6, CI (2.73, 18.41)] setups, suggesting that the HBC setup elicited moderate to large increases in HR compared to the SKIMO and LBC setups. However, no significant difference was found in HR between the SKIMO and LBC setups (p>0.05). Post hoc tests showed similar results for % HR$_{max}$, with statistically significant (p<0.05) changes between the SKIMO and HBC [6.9, CI (3.9, 9.8)] as well as LBC and HBC [5.4, CI (1.4, 9.4)] setups, and no significant differences between the SKIMO and LBC setups (p>0.05). Figure 4c shows mean changes in % HR$_{max}$ between the three equipment setups.
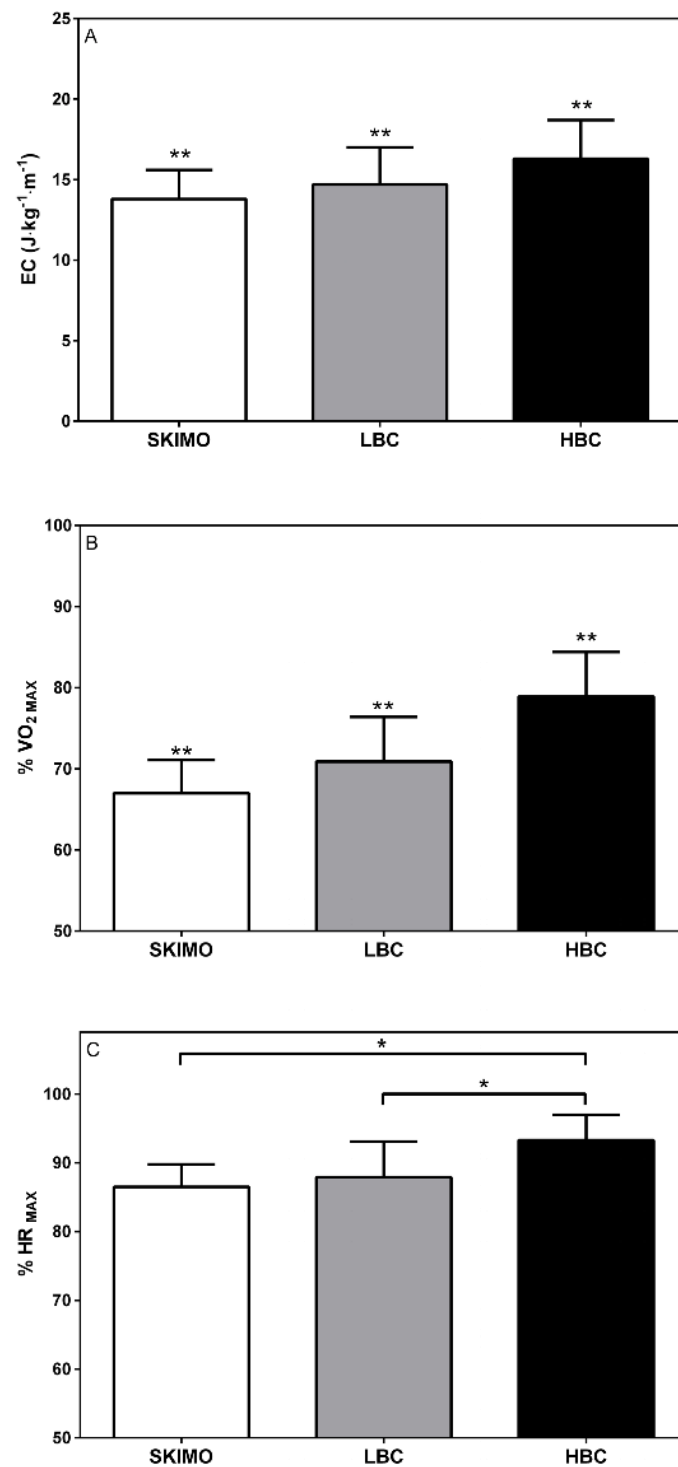
Figure 4. Mean differences in energy cost (4a), percent maximal oxygen uptake (4b), and percent maximal heart rate (4c) between the SKIMO, LBC, and HBC equipment setups. * indicates significant (p<0.05) differences between the two designated setups only. ** indicates significant (p<0.05) differences between all equipment setups.

Discussion

Our findings support the hypothesis that energy cost increases with equipment weight, i.e. using heavier ski touring equipment setups elicits significant increases in oxygen consumption, heart rate and therefore energy cost. However, these observed increases in energy cost were not proportional to the increase in total equipment weight. While the greatest changes were observed between the SKIMO and HBC setups, the most noteworthy differences were found between LBC and HBC setups with averages of 1.6 $J\cdot kg^{-1}\cdot m^{-1}$ higher energy cost, 9% greater relative VO_2, and 5.4% greater relative HR when using the HBC setup compared to the LBC setup. A significant difference in EC was found between the SKIMO and LBC setups, but to a lesser degree ($p = 0.038$) than between the LBC and HBC setups ($p = 0.001$).

These findings show that while there are substantial increases in physiological workload when climbing with heavier ski touring setups, the most profound increases were found between the LBC and HBC setups. With incremental increases in overall setup weight, researchers expected to see proportional increases in EC and other workload markers. However, this significantly larger increase from LBC to HBC setup suggests that setup weight alone is not the only factor influencing EC and efficiency of locomotion during uphill ski touring.

In recent studies, researchers have observed different locomotion components of ski touring and determined how changes in those components affect energy cost and efficiency of uphill skinning. The findings of Schwameder et al.[4] show effects of touring equipment on energy cost similar to those in the current study. They found that mechanical energy required to lift the ski boot was significantly higher when using a frame touring binding similar to those in the HBC setup (3.51 J) compared to a tech binding similar to SKIMO and LBC setups (1.96 J). Their data on locomotion using the three different bindings with identical skis support these findings with significantly higher metabolic cost of using the frame binding compared to the tech bindings. These findings are analogous with results from the current study; though we expected to see an increase in energy cost with setup weight, this increase was greater between the LBC and HBC setups compared to the SKIMO and LBC setups, perhaps due to presence of the frame binding, not just a heavier setup.

Another study using ankle loading to elicit changes in energy cost during uphill skiing showed that with loads of 0.5, 1, and 2 kg added to each ankle, energy cost increased in a linear manner[1]. These researchers found a significant linear relationship ($n = 21$, $r = 0.58$, $p < 0.05$) between ankle loading and EC and expressed their relationship with the following equation: %EC=1.71%weight. In the current study, the LBC and HBC setups increased subject's total weight an average of 2.2% and 5.3% from the SKIMO setups, respectively. Based upon the

aforementioned study, EC increases from the SKIMO setup should have been around 4% for the LBC setups and 9% for the HBC setup. Data shows actual mean energy cost increases from SKIMO to be 6.5% for LBC and 18% for HBC setups. This non-linear increase in EC, with respect to equipment weight, supports the previous statement about the possibility of a factor other than total equipment weight affecting EC.

One substantial difference that should be noted is the method of increasing weight in the study by Tosi et al.[1] compared to the current study, in which weight was added to each setup by changing the actual equipment used. The researchers believe that using heavier equipment more accurately represents changes that would take place with recreational skiers. Tosi et al.[1] also state that effects on energy cost from ankle loading appear negligible for recreational skiers. Based upon the findings of the current study, energy cost during submaximal uphill climbing does, in fact, change with 1.8 and 4.3 kg increases in setup weight. Researchers do agree with the statement by Tosi et al.[1], however, that changes in energy cost in response to increases in equipment weight would be exacerbated in elite-level athletes and during competition when athletes are performing at a significantly higher workload.

During the submaximal bouts in the current study, participants were working at an average of 72 ± 7% of their VO_2max and 89 ±

5% of their HR_{max}. Previous studies examining workload during ski mountaineering races show that well trained and national level competitive ski mountaineers have VO_2max values near 68 mL·kg^{-1}·min^{-1} (compare to 63 ± 11.1 mL·kg^{-1}·min^{-1}) for participants in the current study) and high ventilatory thresholds (VT_2 @ 90% VO_2max compared to VT_2 @ 82 ± 7% VO_2max for participants in the current study) which allow them to perform at high intensities[6-8]. A study examining race time spent between ventilatory thresholds showed that 7% of a ski mountaineering race was spent below VT_1, 51% was spent between VT_1 and VT_2, and 42% was spent above VT_2[5]. These measurements indicate that researchers in the current study were able to keep participants at a workload less than that exhibited during competitive ski mountaineering. This, in conjunction with the results of the current study, further verifies that changes in equipment during recreational ski touring can elicit significant changes in energy cost.

To the researcher's knowledge, this is the second study of its kind to use a treadmill with real skis/skins to examine energy cost and other workload indicators. This methodology was advantageous in providing researchers the ability to conduct maximal tests in a laboratory setting as well as controlling speed, grade, and friction between the skins and the ground—three factors that Tosi et al.[1] suggest could be controlled for in future research. Previous studies have used roller skis modified with

ski touring bindings on treadmills[1-2] or real skis on snow[3,5,8]. The study by Schwameder et al.[4] is the only other study to use touring skis on a treadmill, though it is unclear whether or not skins were used in addition to the skis. Changes in energy cost and other markers of workload observed in the current study demonstrate that increases in ski touring equipment weight of 1.8 kg and 4.3 kg are associated with increases in workload and energy cost. The use of a different boot and binding system for one of the three setups appeared to increase energy cost and heart rate disproportionately compared to the increase in setup weight, suggesting that binding design and distribution of added equipment weight may significantly impact uphill efficiency when ski touring.

While the design of this study gave researchers the ability to control for speed and grade, and to measure relative workloads for each subject, it was not without its limitations. Due to equipment availability, distribution of setup mass and incremental mass differences between touring setups could not be controlled. It should also be noted that, while changes in energy cost between setups are valid, skinning on a treadmill compared to snow might elicit greater energy requirements due to the amount of friction during the forward glide phase of the stride. Participants informally reported that the skis did not glide as easily on the treadmill as they were accustomed to on snow. However, identical skins were used in all three setups, thus controlling for any changes in the friction between the skin and treadmill. The shape and surface area of the skis and skins used during the current study were not controlled. The SKIMO setup used skis with a width of 68mm underfoot that had a cambered profile, while the LBC and HBC setups used a ski with a width of 106mm underfoot and a rockered profile. This difference in shape and construction could have affected the surface area of the skin contacting the treadmill, the associated friction, and potentially the energy cost of locomotion.

The findings of this study add to the relatively sparse literature on the energy cost of ski touring and ski mountaineering; and demonstrate the importance of further research in this field. Future research on ski touring should examine how binding design alone (frame vs. tech) impacts economy in touring setups of identical total weight. Additionally, field tests measuring total energy expenditure during a complete tour would be beneficial to researchers and recreational athletes as a means of determining how these demonstrated changes in energy cost affect performance over the course of a long, real-world ski tour. Finally, quantifying downhill skiing performance of different touring setups would help identify how individual pieces of equipment might be detrimental to uphill efficiency, but beneficial for downhill performance and reliability thereby rationalizing the increased cost of the uphill portion.

Conclusion

It can be concluded that increases in equipment weight are associated with significantly greater energy cost, heart rate, and oxygen consumption during uphill ski touring. Tosi et al.[1] demonstrated that added ankle weight increases energy cost of uphill skiing. However, disproportional increases in workload as well as the findings of Schwameder et al.[4] demonstrate that weight may not be the only factor impacting energy cost of locomotion. Binding design appears to play a substantial role in determining economy and efficiency during uphill ski touring. Further research is needed to verify these claims and to determine the effect of binding design on energy cost of uphill ski touring.

Address for Correspondence

Lance Dalleck, Ph.D., High Altitude Exercise Physiology Program, 600 N. Adams St., Western Colorado University, Gunnison, CO, United States, 81231. Phone: 970-943-3095; Email: ldalleck@western.edu.

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