THE EFFECT OF ADDED POLE MASS ON THE METABOLIC COST OF CROSS-COUNTRY SKIING

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Abstract

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The effect of added pole mass on the metabolic cost of cross-country skiing

Thesis directed by Associate Professor Emeritus Rodger Kram

The optimal length, mass, and stiffness of poles are still a matter of debate in modern cross-country ski racing. Therefore, this study examined the effect of adding pole mass on the metabolic cost and poling frequency during cross-country skiing with the double poling technique. Twelve sub-elite cross-country skiers performed 5-minute roller skiing trials on a motorized treadmill with three different added masses (50g, 100g, 150g) at the center of mass of the pole and with 100g at pole grip. We calculated metabolic rate from the rates of oxygen consumption and carbon dioxide production. We measured poling frequency by counting the number of cycles in 30 seconds twice in each trial and averaged them. Subjects also rated their perceived exertion (RPE) of five different muscle groups (forearm, biceps, triceps, upper back, and lower back). Added mass at the pole shaft significantly increased the oxygen uptake by 1.8% per 100g added and metabolic power by 2.2% per 100g added, while poling frequency significantly decreased by 2.6% per 100g added ($p < .05$). In terms of metabolic cost and frequency, there were no significant differences between added mass at the pole shaft vs. at the pole grip. Participants reported greater RPE (for all muscle groups) when double poling with +100g or +150g on their poles compared to baseline. Further, RPE was significantly greater in all muscle groups (except upper back) when double poling with +100g on each pole shaft vs. 100g at each pole grip**.** In conclusion, during roller skiing adding mass to the center of mass of the pole shaft increases oxygen uptake, metabolic power, and RPE and decreases poling frequency.

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Introduction

During the double poling technique of classical cross-country skiing, 100% of the propulsive forces are applied to the snow via the poles[1,2]. As shown in Figure 1, the skier plants both poles simultaneously into the snow, just in front of their feet and then pushes backwards on the snow to create forward propulsion[3]. The poles are planted nearly vertically[1] and then as the skier moves forward, the angle of the poles moves towards being parallel with the snow surface. The skier also flexes their trunk to aid with propulsion[3]. Next, the recovery phase begins in which the skier extends their trunk and back while simultaneously flexing their shoulders to bring their arms, hands and poles back in front of their body in preparation for the next pole plant. Elite skiers also raise their body center of mass using their leg muscles prior to pole plant[3].

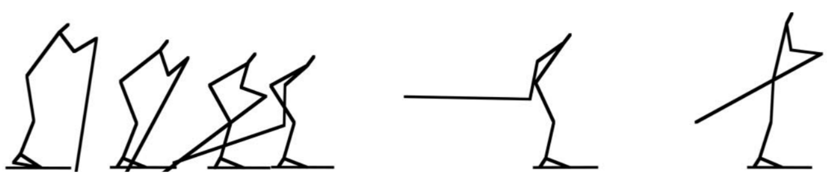

Figure 1 One cycle of the double poling technique[3]

Several properties of cross-country ski poles affect performance. Pole length is probably paramount and is constrained by The Fédération Internationale de Ski rules based on the skier's body dimensions[4]. Specifically, pole length must be < 83% of athlete's height. Onasch et al. and Losnegard et al.[5,6] have both demonstrated that at a fixed skiing velocity, longer poles require less metabolic energy during double poling. In addition to being the right length, ski poles must also be sufficiently strong to avoid breaking and stiff enough to allow effective propulsion. Because the poles are moved rapidly during the recovery phase, intuitively it would seem that lightweight poles with low rotational moment of inertia would be optimal. Because the poles must be rotated during the recovery phase, a unit of mass located more distally on the pole increases the moment of inertia more than the same mass at a proximal pole location, i.e. pole grip. However, there is a trade-off between pole strength and stiffness vs. mass and inertia. It is challenging to create strong and stiff poles that are still lightweight. Although the advantage of lightweight poles seems obvious, to our knowledge, there have been no empirical studies that have quantified the effect of pole mass on performance.

Despite sprint races growing in popularity and prestige, cross-country skiing is traditionally an endurance sport in which the rates of oxygen (maximal values) and energy consumption are the determining factors. Indeed, among athletes in all sports, cross-country skiers have recorded the greatest rates of maximal oxygen consumption ($\dot{V}O_2max$)[7,8]. Skilled technique, snow conditions and equipment (skis, poles, wax etc.) do not affect an athlete's maximal rate of energy consumption. However, those factors profoundly affect the submaximal rate of energy required to ski at a specified velocity and incline (defined as skiing economy[9]). To optimize endurance performance, a cross-country skier must have both a high $\dot{V}O_2max$ and skiing economy. Although, cross-country skiing is a whole´ body form of exercise, particularly in double poling the muscles of the arms, shoulders, and back can fatigue prematurely. One way to asses local muscular fatigue is to use Borg´s Rating of Perceived Exertion scale (RPE)[10].

In other endurance sports (running, cycling), movement frequency affects the submaximal rates of energy required[11,12,13]. For each running velocity or mechanical power output, an individual's freely chosen stride frequency or cadence is generally their most economical cadence[11,12,13]. Pole length affects the freely chosen poling frequency in cross-country skiing; with longer poles, skiers choose slower frequencies[5,6]. However, with a fixed pole length, it is not known if pole mass affects the freely chosen or energetically optimal poling frequency.

Thus, the purpose of this study was to measure the effects of varying pole mass on the metabolic cost and poling frequency of cross-country skiing with the double-pole technique. We proposed two hypotheses: (1) heavier poles will increase metabolic cost, and RPE and decrease poling frequency, and (2) adding mass proximally at the pole grip will use less metabolic power, and RPE and increase the poling frequency compared to same added mass more distally on the pole shaft. To test these hypotheses, we studied subjects roller skiing on a treadmill with ski poles of systematically varied mass and moment of inertia.

Methods

Participants

We analyzed the data from twelve high-caliber cross-country skiers (age= 24.6 ± 6.6 years, mass= 72.8 ± 9.5 kg, height= 1.79 ± 0.08 cm, 10 males, 2 females) who volunteered to participate in this study. All were active competitors ranging from US collegiate level (NCAA) athletes up to World Cup and Olympic Games skiers. All participants used roller skiing as one of their training regimens during the summer period. All of these subjects gave written, informed consent according to the institutional review board of the University of Colorado Boulder.

Experimental protocol

The study comprised two visits. For all testing, we set the custom-made motorized treadmill (3.8kW, length 3.2m, width 0.9m) to an incline of 1.0 degree and at a belt speed of 4.0 m/sec, standard testing conditions used in several previous studies[3, 14]. For safety, participants wore a bicycle helmet and a harness that was secured to an overhead rolling trolley via a slack rope. All subjects used the same pair of roller skis (Pro-Ski Roadline C2, Nyhammar, Sweden) and carbon fiber poles appropriate for their height (83% of height). The metal tips on the ski poles were replaced by rubber pole tips, to which we added a bottom layer of high friction rubber. This modification of the pole tips provided sufficient grip on the treadmill belt without damaging the belt, see Figure 2.

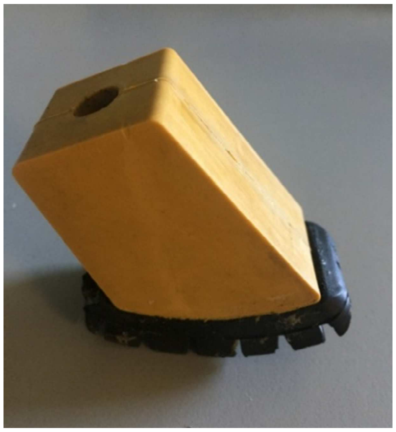

Figure 2 Ski pole rubber tip

To control for the temperature of the roller ski wheels and bearings, we performed our own pilot experiment following the same protocol as the actual experiment. Using an infrared digital thermometer (IR 1000, Klein Tools, Lincolnshire, IL) we confirmed that roller temperature stabilized after a 3 × 5-minute trial warm-up with 5-minute breaks between trials. These findings concur with Ainegren et al.[15] who found that 15 minutes of roller skiing ensured that the roller ski wheels and bearings reached a proper temperature that remained constant throughout subsequent trials.

During the first visit, to familiarize the subjects to treadmill roller skiing, they completed nine, 5-minute trials of roller skiing using the double pole technique with 5 minutes breaks between trials. During the second visit, participants began with three, 5-minute warm-up trials to become even more comfortable with roller skiing on the treadmill and with using the expired gas collection mouth piece. Subjects then roller skied for six, 5-minute trials with 5 minute breaks in between. The first and last trials were always control trials with no mass added to the poles. The middle four trials conditions were randomized and counterbalanced. For three of the trials, we attached either 50g, 100g, or 150g weights to each pole's shaft and for a fourth trial we added 100g to the pole strap. These weights were based on pilot experiments, in which we found that weights greater than 150g were unwieldy.

To add mass, we wrapped the appropriate lead strips around the pole shaft at its center of mass (without grip) such that the lead rested on an adjustable hose clamp (see Fig.3). The hose clamp plus the lead strip equaled the desired added mass for each condition. We also wrapped the added mass with duct tape to prevent any movement of the lead. For a fourth condition, we attached a 100g lead strip to each pole strap and secured it with duct tape.

Figure 3 Pole shaft with lead strip resting on a hose clamp that was tightened to the pole shaft at the center of mass of the pole shaft

We measured the subjects' rates of oxygen uptake and carbon dioxide production using a True One 2400 expired-gas analysis system (Parvo Medics, Salt Lake City, UT). Before each experiment, we calibrated the gas analyzers and pneumotach using reference gases and a calibrated 3-L syringe, respectively. To calculate the metabolic power, we used the Perronet and Massicotte equation[16]. We tested 15 subjects, but with our criteria for acceptable steady-state metabolic data: ≤ 5% difference between the first and last baseline trial and RER values ≤ 1.0, we had to exclude the data of three subjects from our analysis.

We measured the frequency of the poling cycle by counting the number of cycles in 30 seconds twice in each trial and averaged them. We also measured the breathing frequency using the expired gas analysis system. After each experimental trial, we asked the participants to rate their exertion of five different muscle groups individually (forearm, biceps, triceps, upper back, and lower back) using Borg's Rating of Perceived Exertion (RPE) scale (6-20)[10].

Statistics

We present all results as mean ± SD values in the text and mean ± SE in figures. We used linear regression analysis to evaluate and quantify the effects of added pole mass on $\dot{V}O_2$, metabolic power, and poling frequency. To evaluate the effect of added mass on RPE, we performed repeated measures ANOVAs. We also used paired t-tests to evaluate differences between the 100g added mass at the two different locations on the pole. We used a traditional level of significance ($\alpha = 0.05$) and performed all analyses with R software ((version 0.99.892, Boston, MA, USA).

Results

Adding mass at the center of mass of the pole shaft significantly increased the oxygen uptake ($\dot{V}O_2$) compared to the average baseline condition. Per 100g of mass added at the pole shaft, oxygen uptake increased by ~ 1.8% (p = .002, see Figure 4). The average values for each condition are in Table 1. There was no significant difference in oxygen uptake between +100g at the pole shaft and +100g at the pole strap (p = .961).

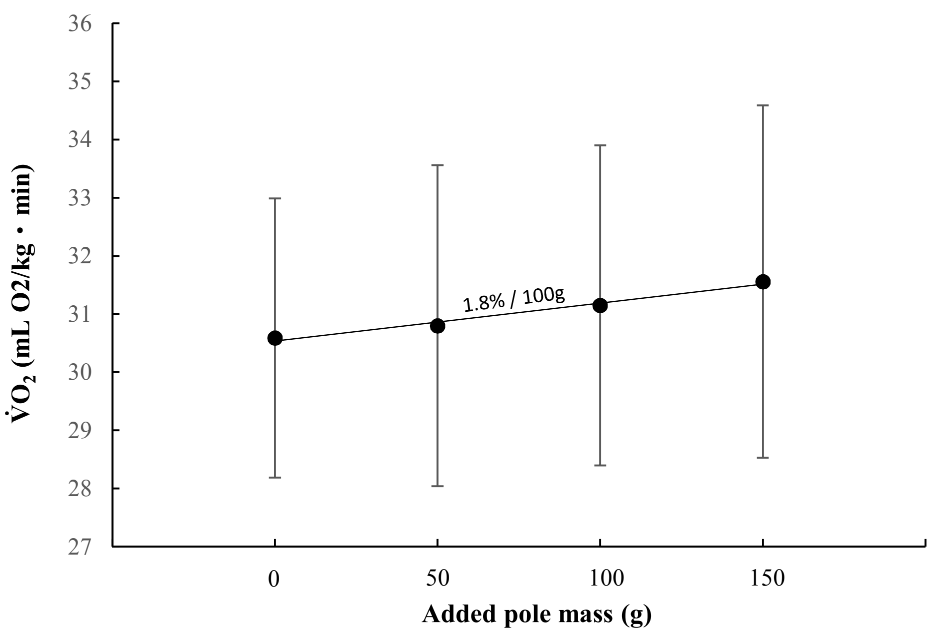

Figure 4 Oxygen uptake for pole shaft added mass conditions. Symbols are the mean values ± SE. Solid line represents the linear regression. $\dot{V}O_2 = 0.006 \times \text{mass} + 30.53$, $R^2 = 0.181$, p = .002

The gross metabolic power followed the same trends as $\dot{V}O_2$, with linear regression confirming a significant positive relation between metabolic power and additional mass (p = .000174). Linear regression of the metabolic power data indicated that per 100g of mass added to the pole shaft, metabolic demand increased by 2.2% (Figure 5). The average gross metabolic power without any mass added was 10.80 W/kg, while for +50g, +100g, and +150g conditions the means were 10.86 W/kg, 11.0 W/kg, and 11.16 W/kg, respectively. Numerically the +100g at the grip condition required slightly less metabolic power than +100g at the pole shaft (11.0 W/kg and 10.85 W/kg, respectively) but the difference was not significant (p = .1452). Numerically with +50g at the pole shaft metabolic power was almost exactly equal to the +100g at the pole strap condition (Table 1).

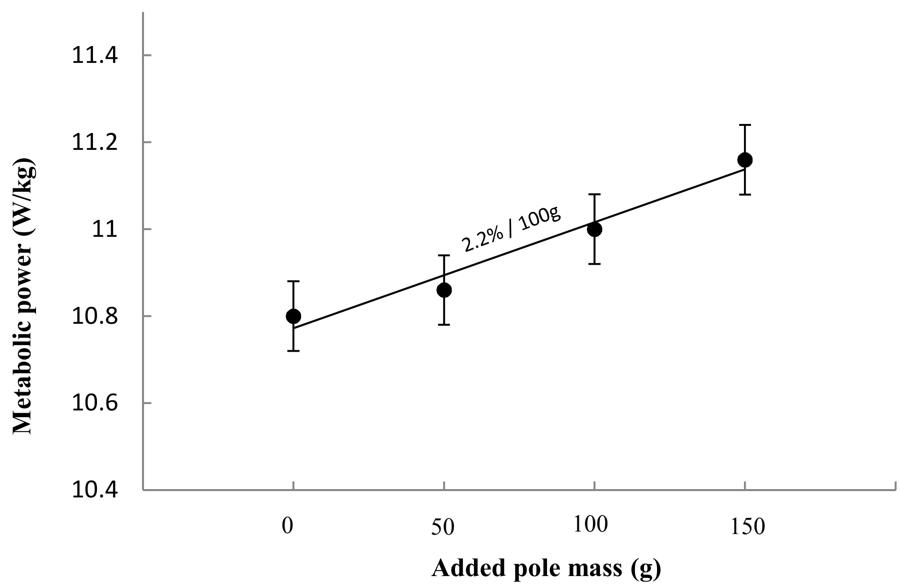

Figure 5 Gross metabolic power for pole shaft added mass conditions. Symbols are the mean values ± SE. Line represents the linear regression. Metabolic power = 0.002 × mass + 10.77, R^2 = 0.266, p = .000174

In response to the added pole mass, subjects chose to use slower poling frequencies. Linear regression of the frequency data showed that per 100g of mass added to the pole shaft, frequency decreased by 2.6% (p = .00113, see Figure 6). The average double poling frequency without any mass added was 44.2 cycles/min and for +50g, +100g, and +150g conditions the averages were 44.0, 43.7, and 42.6 cycles/min, respectively. However, the pole frequency with +100g at the pole shaft was not significantly different than with +100g at the pole strap (43.3 cycles/min, p = .4349).

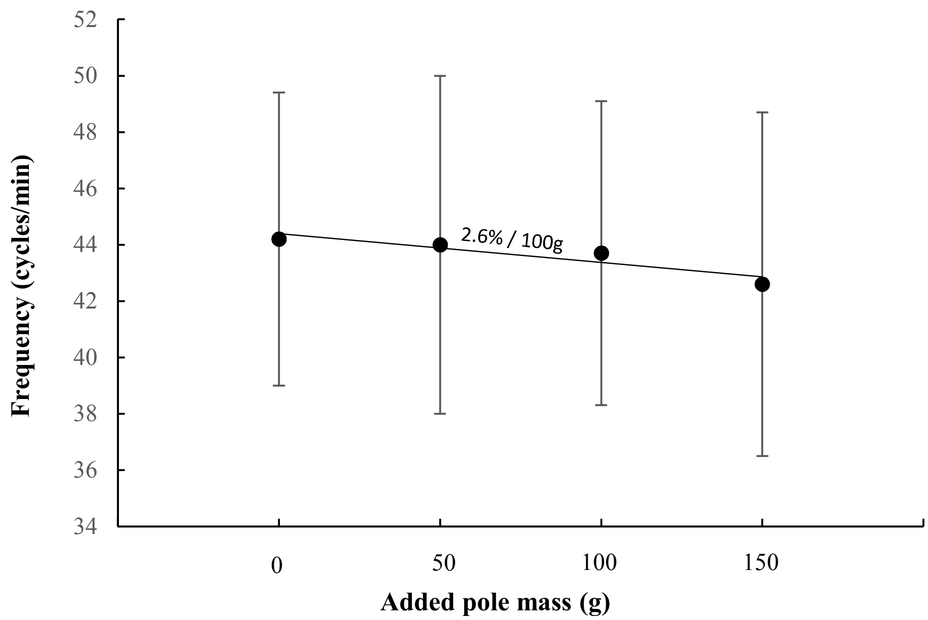

Figure 6 Poling frequency for pole shaft added mass conditions. Symbols are the mean values ± SE. Line represents the linear regression. Frequency = -0.010 × mass + 44.39, $R^2 = 0.2078$, $p < .05$

Table 1 Metabolic power, Oxygen uptake, RER and Frequency, mean (SD)

	Baseline	+50g	+100g	+150g	+100g H
$\dot{V}O_2$(mL O_2/kg·min)	30. 59 (2.40)	30.80 (2.76)	31.15 (2.75)	31.56 (3.03)	30.81 (2.37)
Metabolic power (W/kg)	10.80 (0.87)	10.86 (0.99)	11.00 (0.99)	11.16 (1.11)	10.85 (0.85)
RER	0.89 (0.04)	0.88 (0.03)	0.89 (0.03)	0.89 (0.04)	0.87 (0.04)
Frequency (cycles/min)	44.2 (5.2)	44.0 (6.0)	43.7 (5.4)	42.6 (6.1)	43.3 (5.3)

We also measured the breathing frequency, which we then compared to the poling frequency. The results showed that 5 of the 12 subjects synchronized their breathing frequency with the poling frequency in either a 1:1 or 1:2 ratio. One participant's breathing and poling frequencies were not synchronized in the baseline trials, otherwise he used one breath per each poling cycle.

For the five different muscles groups, participants consistently reported greater exertion (RPE) when double poling with +100g or +150g on their poles compared to baseline. The RPE in the +150g condition was also significantly greater in all muscle groups (except upper back) than the +50g condition. For the +100g condition, participants assigned greater RPE to only their forearms and triceps compared to +50g. Further, RPE was significantly greater in all muscle groups (except upper back) when double poling with +100g on each pole shaft vs. 100g at each pole grip. Mean RPE for all muscle groups are provided in Table 2.

Table 2 RPE values for 5 different muscle groups, mean (SD)

	Baseline	+50g	+100g	+150g	+100g H
Forearm	8.2 (2.9)	9.2 (3.3)	10.2 (3.5)*†	10.5 (3.5)*†	8.8 (3.1)$^{\circ}$
Biceps	8.2 (2.7)	9.1 (3.2)	10.0 (3.4)*	10.5 (3.5)*†	8.9 (3.0)$^{\circ}$
Triceps	9.6 (3.2)	10.1 (3.4)	10.9 (3.7)*†	11.4 (3.7)*†	9.8 (3.2)$^{\circ}$
Upper back	8.3 (1.3)	9.4 (2.0)	9.9 (2.1)*	10.0 (2.1)*	8.7 (1.4)
Lower back	8.0 (1.1)	8.8 (1.6)	9.3 (1.7)*	9.6 (1.6)*†	8.5 (1.2)$^{\circ}$

* different from baseline ($p < .05$), †different from 50g ($p < .05$), ° different from 100g ($p < .05$)

Discussion

Overall, we accept our first hypothesis that heavier poles would increase the metabolic cost of cross-country skiing. The main effect for added mass was significant and the slope of the regression indicated 1.8% and 2.2% increases in $\dot{V}O_2$ and metabolic power, respectively per 100g added per pole. Our observation that $\dot{V}O_2$ and metabolic rate increase with added pole mass supports the intuition of skiers and claims of manufacturers that lightweight poles are advantageous for cross-country skiing performance. Our data for $\dot{V}O_2$ when skiing with normal poles compare well with other studies who tested similar conditions. For example, Onasch et al.[5] found a mean $\dot{V}O_2$ of 38.5 mL O_2/kg·min in sub-elite cross-country skiers double poling at 3.89 m/s up a 1.15° incline. Further, interpolation of the $\dot{V}O_2$ data of Lindiger et al.[17] for double poling by elite cross-country skiers skiing suggests a $\dot{V}O_2$ of ~29mL O_2/kg·min at 4m/s and 1° incline. Our $\dot{V}O_2$ of 30.59 mL O_2/kg·min for the averaged baseline trials is close to the Lindiger et al.[17] value and slightly lower than the value of the Onasch et al. study[5]. That may be due to their lower caliber skiers and/or the slightly steeper incline. Our $\dot{V}O_2$ value is slightly lower than on-snow measurements for sub-elite skiers at controlled speed of 3.94 m/s on flat terrain (37.0mL O_2/kg·min)[17]. That difference may be due to the caliber of skiers tested, the snow/wax conditions or other environmental factors (wind) which could increase submaximal $\dot{V}O_2$.

We also accept our hypothesis that heavier poles would decrease poling frequency. We found a negative relationship between added mass and poling frequency with a regression slope indicating a 2.6% decrease in poling frequency per 100g added per pole. We can compare our results to Losnegard et al.[6] and Lindiger et al.[13] who studied elite skiers double poling at the same or similar (4.17 m/s) speed and at the same 1 degree incline. Their participants poled at 53.6 cycles/min and 41.7 cycles/min, respectively, compared to our participants, who averaged 44.2 cycles/min during the baseline condition. These differences could be due to the type of roller skis and treadmill belts used. Lindiger et al.[19] and our study used Pro-Ski roller skis, while Losnegard et al.[5] used Swenor, which may differ in rolling friction between the skis and treadmill.

We reject our second hypothesis that adding mass proximally at the pole grip would use less metabolic power and increase the poling frequency compared to the same mass added more distally on the pole shaft. Although our data numerically were in those directions, we found no statistically significant differences between the two conditions in $\dot{V}O_2$, metabolic power, or frequency.

Nevertheless, subjects were able to differentiate their perceived exertion between the +100g at the pole shaft and +100g at the pole grip conditions. Subjects perceived greater exertion during skiing with +100g at the pole shaft in all muscles groups, except the upper back. This partially supports our hypothesis, because even though we did not find a significant difference in metabolic power between the +100g conditions at the different locations, subjects were able to feel a difference. It also supports the idea that pole grip mass is less crucial in athlete's performance compared to the added mass of the pole shaft. Further, subjects also perceived the difference between +100g and +150g at the pole shaft compared to baseline, which also partially supports our hypothesis, that heavier poles would increase metabolic cost. However, we have to take into account that subjects were not explicitly blinded to the added mass. They could see if their poles had added mass or not, but the added mass amount was not visible nor mentioned to the subject. Subject awareness of the added mass conditions may have affected their reported RPE values.

It may be illustrative to put the +100g at the pole grip in a context with the actual mass of a ski pole, and of human hand and arm. Racing poles typically have a mass of 56g per m of length, which equates to ~83g per pole for our subjects based on their averaged pole length (1.485 m). Therefore, adding 100g to each pole grip increases the mass of the pole by 120%. Based on DeLeva[20], an average male's hand comprises 0.61% of total body mass. For our participants, that equates to an average hand's mass of 444g. Comparing an average hand's mass with +100g at the pole grip condition, we see that 100g is only 22.5% percent of the hand's mass. Further, an average male's arm is 4.94% of body mass[20]. For our participants, average arm mass was 3.6 kg. When we compare the +100g at the pole grip with the average arm mass, we see that +100g is only 2.78% of the arm's mass. Thus, adding 100g to the pole grip is almost negligible in a comparison with the whole arm, although we increased the total pole mass by

120%. This fact then can partially explain why +100g, one quarter of a hand's weight, at the pole strap did not significantly increase the $\dot{V}O_2$ or metabolic power.

Some but not all skiers synchronized their breathing frequency with their double poling frequency. This is in contrast with previous ski studies; both Lindiger et al.[17] and Fabre et al.[20] reported that all skiers inhale during pole recovery and exhale as they push back with the poles, with a 1:1 ratio. These studies support the overall phenomena of locomotion – respiration coupling, which was has been found in animals[21,22] as well as in humans[23,24,25]. Lindiger et al.[17] found that subjects skiing at 40 cycles/min kept their breathing frequency the same (1:1 ratio) at both slow and fast speeds. However, skiers poling at 60 or 80 cycles/min used one breath per two cycles or were even desynchronized at slower speeds, but at faster speeds they went back to a 1:1 ratio. Therefore, further research on breathing frequency during double poling is needed to clarify the interaction between breathing frequency, exercise intensity, and poling frequency.

Although it may at first seem unrelated, it is instructive to consider the effect of adding mass to running shoes. Comparison of our results with previous studies of running shoes shows a similar pattern. Frederick et al.[26] observed a $\dot{V}O_2$ increase of ~1.0% per 100g added mass per shoe, which is approximately half of our increase of 1.8% per 100g added at the pole shaft. The difference, that double poling requires almost a double amount of $\dot{V}O_2$ per +100g, may be explained by the size and strength of the muscle groups involved in these specific motions or the location of the added mass. During running, we primarily use lower limb muscles, which involve the quadriceps, hamstring, hip flexors, calf muscles etc. However, in double poling, we primarily use arm and upper body muscles, which tend to be smaller and weaker than lower limb muscles[27]. Unlike ski poles, adding mass to running shoes only slightly decreases cycle frequency, <1% per +200g per shoe[28].

There were several limitations of our study. Roller skiing on a treadmill is not exactly the same as cross-country skiing on snow due to differences in the surface (treadmill vs. snow) and in the equipment (roller skis vs. skis). Further, subjects used their own ski poles, which varied in length (according to their height) and therefore in their pole weight. Ideally, we would have recruited subjects all of the same height with the same pole length to eliminate this issue. Our findings were also limited to just one speed and one incline. Therefore, future studies should investigate different speeds and different inclines to quantify the overall effect of added pole mass on performance. Another important note is that we studied pole mass effects only during double poling, but the effects could differ in other ski techniques, such as classic diagonal striding. We were able to analyze data only two female participants due to our stringent exclusion criteria for aerobic fitness.

Further, we found no difference between adding mass at the pole grip or on the pole shaft, which is counter-intuitive. Future research should more thoroughly investigate the effect of added mass at different locations on the pole on metabolic cost. One could add the same mass at three different locations on the pole (pole grip, center of mass, pole tip) and compare them to see at which location the added mass is more energetically demanding. We did not establish which is more crucial to athlete's performance; pole mass or pole stiffness. Therefore, future studies should systematically vary pole stiffness without changing mass. Based on our results, even if ski poles could be made "massless" they would only reduce the metabolic cost of double poling by 1.5%. Perhaps, ski pole manufacturers should not focus so much on pole mass given the small potential marginal gains. Our study focused on the effect of mass added to the poles, but future research should examine the effects of mass added to skis or ski boots on the metabolic cost of skiing, because manufactures and skiers always want to improve performance.

In conclusion, adding mass to the center of mass of the pole shaft increases oxygen uptake, metabolic power, and RPE and decreases double poling frequency. Overall we confirm the intuition that lightweight poles can help to improve athlete's performance.

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