Steeper or Faster? Tactical Dispositions to Minimize Oxygen Cost in Ski Mountaineering

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Purpose: Investigate the effect of speed, inclination, and use of heel elevator on the oxygen cost of vertical climbing ($C_{\text{vert}}$) in ski mountaineering.

Methods: In this study, 19 participants who were (3 women and 16 men) moderate- to well-trained recreational Norwegian ski mountaineers were involved. All participants were tested for VO$_{2\text{max}}$ in running, and in a ski mountaineering test on a treadmill, to assess $C_{\text{vert}}$. The test protocol consisted of 12 4 min work periods at different inclinations from 13 to 23°, with continuous VO$_2$ measurements. After every second work period, the inclination increased by 2°, and speed was decreased accordingly. The speed reduction was based on the equation $V_{\text{vert}} = \text{speed} \cdot \sin(\alpha)$, where $\alpha$ represents the angle of inclination. $V_{\text{vert}}$ was thus held constant for each work period (854 m·h$^{-1}$). All work periods were completed twice, with and without a heel elevator. Half of the subjects started with the smallest inclination, and the other half started with the steepest inclination.

Results: The results showed that $C_{\text{vert}}$ was unchanged at all inclinations except 13°, where there was a significantly higher $C_{\text{vert}}$, at the same $V_{\text{vert}}$. Only at 13°, $C_{\text{vert}}$ was higher with the use of heel elevator. There was also a significant trend indicating lower $C_{\text{vert}}$ with use of heel elevator with steeper inclination.

Conclusions: There seemed to be nothing to gain by choosing detours if the inclination was 13° or less. The use of heel elevator was more advantageous, the steeper the inclination, but at 13° there was a negative effect of using heel elevator.

Keywords: ski mountaineering, work economy, vertical speed, heel elevator, route selection

INTRODUCTION

Competitive ski mountaineering involves both uphill and downhill sections. The duration of the competition is relatively long, from 30 to 600 min (Gallaerts et al., 2018). It involves altitude gains of ~80 m in a sprint, up to ~2,000 m in long individual races (Bortolan et al., 2021), with a mean duration of 101 min with an intensity of 93% maximal heart rate ($HR_{\text{max}}$) (Duc et al., 2011). Compared to for example cross-country skiers, ski mountaineers are relatively heavy equipped, wearing both rucksack and helmet in addition to ski mountaineering skis and boots. However, skis and boots would not add considerable weight compared to cross country equipment, with a minimum weight of 1 kg per pair of boots and a minimum weight of 1.5 kg per pair of skis in ski mountaineering (Bortolan et al., 2021). Race time has been found to correlate well with maximal
oxygen consumption ($\text{VO}_\text{2max}$), indicating ski mountaineering to be a typical aerobic endurance sport (Duc et al., 2011). Also, in ultra-alpine running, aerobic endurance sports in previous studies (Størren et al., 2013, 2014; Sunde et al., 2019; Johansen et al., 2020, 2021) have been shown to depend on the maximal aerobic capacity ($\text{VO}_\text{2max}$). However, previous studies have not investigated the effect of heel elevators on $\text{C}_\text{vert}$ at a constant $\text{V}_\text{vert}$ and that the use of heel elevator would improve $\text{C}_\text{vert}$ at the steepest inclinations.

**METHODS**

**Subjects**

The study involved 19 (3 women and 16 men) moderate-to well-trained 32.6 ± 11.1-year-old recreational Norwegian ski mountaineers who participated in this study (Table 1). No measurements of $\text{C}_\text{vert}$ with ski mountaineering equipment had previously been done prior to this study. Based on measurements in mechanical efficiency, by Praz et al. (2016a), on roller skies at low vs. medium inclinations, we calculated the sample size. Given a mean difference in the mechanical efficiency of 13% between inclinations of 10 and 14°, a sample size of 16 participants would be needed. Nineteen participants were recruited to account for possible withdrawals. The study was approved by the institutional research board at the University of Southeastern Norway, the Norwegian Centre for Research Data (NSD), and conducted in accordance with the Helsinki declaration. All subjects gave their written consent to participate, after having received information about the study.

**Test Procedures**

The subjects were tested over two different days. Day one consisted of an incremental running $\text{VO}_\text{2max}$ test. $\text{VO}_\text{2max}$ was tested partly to obtain information on the participants’ aerobic capacity per se, and also to investigate if $\text{VO}_\text{2max}$ could have any impact on $\text{C}_\text{vert}$. The subjects started at an intensity of 8–12 km·h$^{-1}$ and a 5.3% inclination. Every 30 s the speed was increased by 0.5 km·h$^{-1}$. The test terminated at voluntary fatigue, and additionally heart rate (HR) ≥ 98 % of HR$_\text{max}$, respiratory exchange ratio (RER) ≥ 1.05, as well as a plateau of the $\text{VO}_2$ curve, was used to evaluate if $\text{VO}_\text{2max}$ was obtained (Åstrand et al., 2003). The mean of the three subsequent highest registered $\text{VO}_2$-values, each representing 10 s intervals by the mixing chamber, was set as $\text{VO}_\text{2max}$. All $\text{VO}_2$ measurements were made by the metabolic test system, Metalyzer II Cortex (Biophysic GmbH, Leipzig, Germany), with a mixing chamber. The treadmill used for running was a Woodway PPS 55 sport

**TABLE 1 | Characteristics of skiers.**

| All ($N = 19$) | Females ($N = 3$) | Males ($N = 16$) |
|----------------|------------------|-----------------|
| BW (kg)        | $75.9 \pm 10.5$  | $59.5 \pm 5.7$  | $79.9 \pm 7.2$ |
| Age (yrs)      | $32.6 \pm 11.1$  | $35.3 \pm 3.5$  | $32.7 \pm 12.2$ |
| $\text{VO}_\text{2max}$ (mL·kg$^{-1}$·min$^{-1}$) | $57.2 \pm 6.1$ | $54.3 \pm 5.8$ | $58 \pm 6.3$ |

Values are mean ± standard deviation. BW, body weight; $\text{VO}_\text{2max}$, maximal oxygen uptake in running; mL·kg$^{-1}$·min$^{-1}$, milliliters oxygen per kilogram body weight per minute.
(Waukesha, USA). All HR measurements were made by Polar s610 HR monitors (Kempele, Finland).

The second day of testing consisted of a ski mountaineering test on a cross-country skiing treadmill (Rodby RL 2700E, Rodby Innovation, Vänge, Sweden). Ski mountaineering equipment, including skis, boots, poles, and a rucksack of 4 kg, was used on the treadmill. The subjects were acquainted with the cross-country skiing treadmill by use of a 10-min submaximal workout ahead of the test. The test protocol consisted of twelve 4 min work periods with maximal 30 s breaks in between. All work periods were completed twice, with the heel elevator lifted (6.1 cm) every second work period. After every second work period, speed was decreased and inclination increased, or vice versa. This resulted in the same V<sub>vert</sub> for all periods (Table 2). V<sub>vert</sub> was calculated from the trigonometric function V<sub>vert</sub> = speed · sin(α), were α represents the angle of inclination.

Vertical speed (V<sub>vert</sub>) was set to correspond to a relatively fast ski mountaineering speed (854 m<sub>vert</sub>·h<sup>−1</sup> equivalent to 14.2 m<sub>vert</sub>·min<sup>−1</sup>). Oxygen consumption, HR, and cycle frequency (CF) were measured continuously during all 12 work periods. Borg scale was registered immediately after completing each work period. All tests at test day 2 were performed with the Jaeger Vyntus CPX with a mixing chamber, measuring every 20 s (CareFusion, GmbH, Hoechberg, Germany).

The duration of the test was ~55 min. In order to evaluate if changes in HR, VO<sub>2</sub>, and Borg scale was a result of the long duration of the test, or a result of the change of speed and inclination, half of the subjects started with the smallest inclination (work period 1, 2, 3, etc.), and 50% started with the steepest inclination (work period 12, 11, 10, etc.).

**Data Processing and Statistical Analyses**

Oxygen consumption and HR was calculated as the average of three measurements in minute 3–4 (3:00, 3:20, and 3:40). VO<sub>2max</sub> was set as the mean of the three subsequent highest registered VO<sub>2</sub>-values. CF was registered manually by counting the number of strides from minute 2:00 to 2:30 and multiplied by two in order to get stride · min<sup>−1</sup>.

Normality was tested by the use of QQ-plots and Shapiro-Wilk (p = 0.313) and found to represent normal distributions for the main variable (C<sub>vert</sub>). Values were thus expressed descriptively as mean ± SD. Correlations between C<sub>vert</sub>, CF and VO<sub>2max</sub> were expressed as the correlation factor r from Pearson’s bivariate tests. Based on the correlation coefficient definitions by Hopkins (2000), we have defined strong correlations to be r < 0.7 in the present study. Also, in order to detect possible patterns between inclination and work economy, and between velocity and work economy, a general linear model (GLM) with Tukey post-hoc tests was performed. Statistical analyzes were performed using the software program statistical package for social science version 26 (SPSS, IBM, Chicago, IL, USA). A p < 0.05 was accepted as statistically significant in all tests.

**RESULTS**

**The Effects of Speed and Inclinations on C<sub>vert</sub>**

All results are presented on a group level in Table 2. There was no significant change (p = 0.1) in C<sub>vert</sub> with increasing inclination when not correcting for the use of heel elevator. However, when corrected for heel elevation there was a significant improvement in C<sub>vert</sub> with increased elevation (p = 0.02). When comparing the work period at 13<sup>°</sup> with all the other inclinations, there was a significant (p < 0.01) higher C<sub>vert</sub> at 13<sup>°</sup>.

**The Effect of Heel Elevation on C<sub>vert</sub>**

When comparing differences in C<sub>vert</sub> related to the use of heel elevators, there was a significant trend (p < 0.01) using heel elevators with increasing inclination. At 13<sup>°</sup> the post hoc analyzes showed that C<sub>vert</sub> was significantly (p < 0.01) worse with the use

**TABLE 2 | Physiological results from sub-maximal workloads (N = 19).**

| Work period | Inclination (°) | V (km h<sup>−1</sup>) | Heel elevator (cm) | HR (b min<sup>−1</sup>) | CF (s min<sup>−1</sup>) | VO<sub>2</sub> (mL kg<sup>−1</sup> min<sup>−1</sup>) | RPE | C<sub>vert</sub> (mL kg<sup>−1</sup> m<sup>−1</sup>) |
|-------------|----------------|----------------------|-------------------|---------------------|------------------------|---------------------------------|-----|---------------------|
| 1           | 13             | 3.8                  | 0.0               | 167 ± 15            | 82 ± 7                 | 44.7 ± 3.3                      | 15 ± 3  | 3.14 ± 0.23*       |
| 2           | 15             | 3.0                  | 6.1               | 170 ± 14            | 85 ± 8                 | 46.6 ± 2.8                      | 15 ± 3  | 3.28 ± 0.20*       |
| 3           | 15             | 3.2                  | 0.0               | 168 ± 15            | 72 ± 8                 | 43.2 ± 2.9                      | 14 ± 2  | 3.03 ± 0.21        |
| 4           | 17             | 2.9                  | 0.0               | 167 ± 16            | 68 ± 6                 | 42.4 ± 2.6                      | 14 ± 2  | 2.98 ± 0.18        |
| 5           | 17             | 2.9                  | 6.1               | 168 ± 16            | 71 ± 6                 | 42.1 ± 2.3                      | 14 ± 2  | 2.96 ± 0.16        |
| 6           | 19             | 2.6                  | 0.0               | 167 ± 16            | 65 ± 6                 | 42.6 ± 2.3                      | 14 ± 2  | 2.99 ± 0.16        |
| 7           | 19             | 2.6                  | 6.1               | 167 ± 16            | 66 ± 9                 | 41.6 ± 2.0                      | 14 ± 2  | 2.92 ± 0.14        |
| 8           | 21             | 2.4                  | 6.1               | 167 ± 16            | 65 ± 5                 | 42.5 ± 1.9                      | 15 ± 2  | 2.98 ± 0.14        |
| 9           | 21             | 2.4                  | 0.0               | 167 ± 17            | 63 ± 6                 | 41.4 ± 2.1                      | 14 ± 2  | 2.91 ± 0.15        |
| 10          | 23             | 2.2                  | 6.1               | 165 ± 18            | 63 ± 7                 | 43.0 ± 2.1                      | 15 ± 3  | 3.02 ± 0.15        |
| 12          | 23             | 2.2                  | 6.1               | 165 ± 18            | 63 ± 7                 | 41.5 ± 2.3                      | 14 ± 2  | 2.91 ± 0.16        |

Vertical velocity (V<sub>vert</sub> measured as m<sub>vert</sub>·h<sup>−1</sup>) was held constant at 854 m<sub>vert</sub>·h<sup>−1</sup> in all work periods. Values are mean ± standard deviation (SD), °, degrees; V, speed; km h<sup>−1</sup>, kilometer per hour; HF, heart frequency; b min<sup>−1</sup>, beats per minute; CF, cycle frequency; s min<sup>−1</sup>, steps per minute; VO<sub>2</sub>, oxygen uptake; mL kg<sup>−1</sup> min<sup>−1</sup>, milliliters per kilogram bodyweight per minute; RPE, rate of perceived exertion measured by Borg scale; C<sub>vert</sub>, oxygen cost of vertical displacement; mL kg<sup>−1</sup> m<sup>−1</sup>, milliliter oxygen per kg bodyweight per vertical meter. *p < 0.01: higher than in all other inclinations. #p < 0.01: worse effect of heel elevator than in all other inclinations. §p < 0.01: lower C<sub>vert</sub> with increased inclination.
of the heel elevator compared to all other inclinations. The results for $C_{\text{vert}}$ with or without heel elevators are presented in Figure 1.

**Associations Between Cycle Frequency, Rate of Perceived Exertion, Heart Rate, and $C_{\text{vert}}$**

CF decreased significantly ($p < 0.01$) with an increase in inclination and decrease in speed. However, there was no correlation ($r = 0.27$) between CF and $C_{\text{vert}}$. There were no correlations at any inclinations between running VO$_{2\text{max}}$ and $C_{\text{vert}}$ or between running VO$_{2\text{max}}$ and CF.

There was no change in RPE or HR throughout the 12 work periods for the whole group.

**DISCUSSION**

**Main Findings**

The main findings of the present study were that $C_{\text{vert}}$ was unchanged at all inclinations except 13°, where there was a significantly higher $C_{\text{vert}}$ when tested with the same $V_{\text{vert}}$ (854 m·h$^{-1}$). When corrected for heel elevator there was a significant trend between increased inclination and a decrease in $C_{\text{vert}}$. The use of heel elevator was more advantageous, the steeper the inclination with no positive effect at 13°.

**The Effects of Speed and Inclinations on $C_{\text{vert}}$**

Typical speed during guided ski mountaineering as a leisure activity is normally ~400 and 600 m$_{\text{vert}}$·h$^{-1}$ when guiding experienced groups. During competing ski mountaineering, the $V_{\text{vert}}$ could differ from ~550 to 900 m$_{\text{vert}}$·h$^{-1}$ (Tosi et al., 2009; Duc et al., 2011; Praz et al., 2014). This means that the chosen $V_{\text{vert}}$ in the present study (854 m$_{\text{vert}}$·h$^{-1}$) corresponds to competitive ski mountaineering and not ski mountaineering as a leisure activity. To keep the chosen $V_{\text{vert}}$ in this study, the speed at 13° had to be high (3.8 km·h$^{-1}$), probably higher than most of the participants were familiar with. When the inclination decreases, speed must increase in order to maintain the same $V_{\text{vert}}$. The increase in V per decrease in degrees is exponential. Because of this, speed was unproportionally high at 13° and this may have caused the high $C_{\text{vert}}$ at this inclination. This $V_{\text{vert}}$ is equivalent to 4.1 km·h$^{-1}$ at 11.9°. The chosen $V_{\text{vert}}$ in the

![Figure 1](https://example.com/figure1.png)

**Figure 1** | Cost of vertical climbing ($C_{\text{vert}}$) for all 12 work periods with and without heel elevator divided into a total of six different inclinations. $C_{\text{vert}}$, cost of ski mountaineering; ml kg$^{-1}$·m$^{-1}$, milliliter oxygen per kg bodyweight per minute per vertical meter, incline; °, degrees. *p < 0.01: higher than in all other inclinations. #p < 0.01: worse effect of heel elevator than in all other inclinations.
present study thus represents a higher speed than the optimal speed of 3.3 km·h⁻¹ at 11.9°, presented in Tosi et al. (2010). Comparably, the same \( V_{\text{vert}} \) as in the present study would have resulted in a speed of 8.6 km·h⁻¹ at 5.7° in the study by Praz et al. (2016a). However, the highest speed at 5.7° in Praz et al. (2016a), was 6 km·h⁻¹. Although the principles in this comparison may be valid, caution should be taken regarding the actual speeds, as both Tosi et al. (2010) and Praz et al. (2016a) used rollerskis. In other words, there seemed to be some sort of threshold between 13 and 15° where increased speed would lead to impaired \( C_{\text{vert}} \). The present results should be considered specifically for ski mountaineering. In, e.g., alpine running, Savoldelli et al. (2017) found a more continuous reduction of \( C_{\text{vert}} \), the steeper the inclination without a marked threshold.

Praz et al. (2016a,b) did not find any changes in \( C_{\text{vert}} \) with changes in speed up to ~6° but found that \( C_{\text{vert}} \) decreases with increasing speed at steeper inclinations. The present study did not investigate different speeds at the same inclinations, but rather different inclinations at the same \( V_{\text{vert}} \). This makes direct comparisons somewhat difficult.

The Effect of Heel Elevation on \( C_{\text{vert}} \)

The present results displayed a larger gain from using heel elevators the higher the inclination. At 13° the effect of heel elevator was negative and significantly worse than at all other inclinations. These results provide novel data on the use of heel elevators at different inclinations, and we suggest not to use heel elevators at 13° or less inclination. No previous studies have investigated the effects of heel elevators on \( C_{\text{vert}} \) at different inclinations. Comparisons with previous studies are therefore difficult.

Cycle Frequency and \( C_{\text{vert}} \)

Mean CF in the present study ranged from 61 to 85 strides·min⁻¹, increasing with increasing speed. 85 strides·min⁻¹ was thus obtained at 3.8 km·h⁻¹. In Praz et al. (2016a) mean CF ranged from 29 to 47 strides·min⁻¹, with 47 strides·min⁻¹ at 6 km·h⁻¹. However, the skiers in Praz et al. (2016a) were using roller skies, probably explaining the lower CF. In a recent study by Lasshofer et al. (2021), CF was measured during an incremental test at 14°. Mean CF in that study was 97 strides·min⁻¹, with 137 strides·min⁻¹ at the highest speed of 6.9 km·h⁻¹. These results taken together may indicate that CF increases with increasing speed when using ski mountaineering equipment as opposed to roller skis on a treadmill. In the present study, CF decreased significantly with an increase in inclination and decrease in speed, but there was no correlation \((r = 0.27)\) between CF and \( C_{\text{vert}} \). There were also no correlations at any inclinations between the subject’s condition measured as \( \text{VO}_{2\text{max}} \) in running and CF. The participants in the present study may be characterized as a homogenous group regarding ski mountaineering experience. It seems that they subconsciously chose the most effective CF based on their previous experiences.

Tosi et al. (2010) suggested that higher CF resulted in a higher total work at a given speed. In opposition to the results in Tosi et al. (2010), there were relatively small variations in CF in the present study, expressed by coefficients of variance (CV) between 8 and 13% in the 12 work periods.

Limitations and Practical Implications

At the chosen speed it looks like route selection does not matter relative to \( C_{\text{vert}} \) given inclinations between 15 and 23°. It must be emphasized that 854 m·h⁻¹ is a relatively fast competition speed that requires a good shape to maintain over a long time. It is conceivable that testing at lower speeds could have yielded different results.

The present study showed a significant trend indicating lower \( C_{\text{vert}} \) with the use of heel elevators with steeper inclination. There are nevertheless individual differences. As shown in Table 2, quite a few of the participants are profiting at 17°, and some are already at 15°. It may therefore be appropriate on an individual basis, to test both with and without heel elevation at inclinations between 15 and 19°, to evaluate what is perceived as most effective.

In running and cycling, Storen et al. (2008) and Sund et al., 2010, respectively, discussed that improvement in oxygen cost corresponded to an equivalent better time performance. The difference between \( C_{\text{vert}} \) at 13° and the mean \( C_{\text{vert}} \) in all the other inclinations was 6.5%. A 6.5% improvement in \( C_{\text{vert}} \) could therefore correspond to a 6.5% improvement in ascent time performance in a ski mountaineering competition. Duc et al. (2011) showed that during a ski mountaineering race with two uphill sections and a total duration of 95, 11 min was descents and 44 ascents. This means that a 6.5% improvement in \( C_{\text{vert}} \) could provide an improved overall time performance of ~3 min.

Future Perspectives

Future studies should analyze time performance both in the lab and in the field, to detect correlations between vertical MAS, \( C_{\text{vert}} \), \( \text{VO}_{2\text{max}} \), and time performance in the uphill sections of ski mountaineering. Also, the relevance and strong validity of field testing are valuable despite the challenges of the variations in the snow- and weather conditions, steepness and sloping terrain in test tracks, change of use of muscles at each turn, and so forth. Laboratory-based tests will never be 100% equal to ski mountaineering at snow but have the advantage of being able to standardize and ensure equal conditions from test to test.

Considering this study found that the use of heel elevator was more advantageous the steeper the inclination, it would be interesting to analyze how the use of heel elevator affects both the way the muscles work and biomechanical factors.

It could also be interesting to analyze how changes in e.g., maximal leg strength affects \( C_{\text{vert}} \). Previous studies have revealed improvements of ~5% in oxygen cost after maximal strength training in both cross country skiing (Osterås et al., 2002), running (Storen et al., 2008), and cycling (Sunde et al., 2010). In these studies, a decrease in oxygen cost led to a corresponding improvement in time performance. This may mean that if ski mountaineers add a relatively small amount of maximal strength training in, e.g., half squat, it could lead to better performance. Controlled interventions targeting adaptations in \( \text{VO}_{2\text{max}} \), and the consequent impact on-time performance and \( C_{\text{vert}} \) would also be of great interest. The suggested future investigations
would also benefit from investigating potential sex differences in tactical dispositions related to $C_{\text{vert}}$. Also, the incorporation of accelerometers to determine the energy expenditure during ski mountaineering could further add help to the tactical dispositions. To better understand this topic, it is suggested to read (e.g., Crouter et al., 2006; Kinnunen et al., 2019; Afq et al., 2020).

**CONCLUSIONS**

$C_{\text{vert}}$ was unchanged at all inclinations except 13°, where there was a significantly higher $C_{\text{vert}}$ when tested with the same $V_{\text{vert}}$ (854 m·h$^{-1}$). When corrected for heel elevator there was a significant trend between increased inclination and a decrease in $C_{\text{vert}}$. The use of heel elevator was more advantageous, the steeper the inclination with a negative effect at 13°.

Therefore, it seemed to be nothing to gain by choosing detours or heel elevator if the inclination is 13° or less.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article-supplementary material, further inquiries can be directed to the corresponding author.

**REFERENCES**

Åstrand, P. O., Rodahl, K., Dahl, H. A., and Stromme, S.B. (2003). *Textbook of Work Physiology: Physiological Bases of Exercise*, 4th Edn. Champaign, IL: Human Kinetics.

Afaq, S., Loh, M., Kooner, J., and Chambers, J. (2020). Evaluation of three accelerometer devices for physical activity measurement amongst South Asians and Europeans. *Phys. Act. Health* 4, 1–10. doi: 10.5334/pahh.46

Barrett-O’Keefe, Z., Helgerud, J., Wagner, P. D., and Richardson, R. S. (2012). Maximal strength training and increased work efficiency: contribution from the trained muscle bed. *J. Appl. Physiol.* 13, 1846–1851. doi: 10.1152/japplphysiol.00761.2012

Bortolan, L., Savoldelli, A., Pellegrini, B., Modena, R., Sacchi, M., Holmberg, H.-C., et al. (2021). Ski mountaineering: perspectives on a novel sport to be introduced at the 2026 Winter Olympic Games. *Front. Physiol.* 21, 737249. doi: 10.3389/fphys.2021.737249

Crouter, S. E., Clowers, K. G., and Bassett Jr, D. R. (2006). A novel method for studying are included in the article/supplementary

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The original contributions presented in the study are included in the article-supplementary material, further inquiries can be directed to the corresponding author.

**ETHICS STATEMENT**

The studies involving human participants were reviewed and approved by the Institutional Research Board at the University of Southeastern Norway and the Norwegian Centre for Research Data (NSD). The patients/participants provided their written informed consent to participate in this study.

**AUTHOR CONTRIBUTIONS**

AS: planning, testing, and writing. FC: testing and contributed to the writing. OS: supervisor and contributed to the writing. All authors contributed to the article and approved the submitted version.

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Støren, Ø., Ulevåg, K., Larsen MH, Støa, E. M., and Helgerud, J. (2013). Physiological determinants of the cycling time trial. *J. Strength Cond. Res.* 27, 2366–2373. doi: 10.1519/JSC.0b013e31827f5427

Sunde, A., Johansen, J.-M., Gjøra, M., Paulsen, G., Bråten, M., Helgerud, J., et al. (2019). Stronger is better: the impact of upper body strength in double poling performance. *Front. Physiol.* 10, 1091. doi: 10.3389/fphys.2019.01091

Sunde, A., Støren, Ø., Bjerkaas, M., Larsen, M. H., and Hoff, J., Helgerud (2010). Maximal strength training improves cycling economy in competitive cyclists. *J. Strength Cond. Res.* 24, 2157–2165. doi: 10.1519/JSC.0b013e3181aeb16a

Tosi, P., Leonardi, A., and Schena, F. (2009). The energy cost of ski mountaineering: effects of speed and ankle loading. *J. Sports Med. Phys. Fitness* 49, 25–29.

Tosi, P., Leonardi, A., Zerbini, L., Rosponi, A., and Schena, F. (2010). Energy cost and efficiency of ski mountaineering. A laboratory study. *J. Sports Med. Phys. Fitness* 50, 400–406.

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