Experimental underpinning for predicting oxygen demand using roller skiing kinematics

The model used to predict oxygen demand ($\dot{V}O_2^{\mathrm{dem}}$) from propulsive power (P_{prop}) and skiing speed (v) in the current study is based on the following hypotheses:

H.I $\dot{V}O_2^{\mathrm{dem}}$ increases linearly with v at constant P_{prop}.

H.II $\dot{V}O_2^{\mathrm{dem}}$ does not depend on the type of work done at constant v.

This appendix presents the results of two experiments that could falsify these hypotheses. Specifically, experiment 1 explores H.I by varying treadmill speed and inclination, keeping P_{prop} constant, and experiment 2 explores H.II by varying the work done against gravity and rolling resistance, keeping skiing speed constant.

I. METHODS

All measurements presented here were completed at sub-maximal exercise intensities, and $\dot{V}O_2^{\mathrm{dem}}$ was defined as the steady-state $\dot{V}O_2$ at the end of a 5 minute load at a constant work rate. Oxygen consumption was measured using an automatic ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany). In experiment 2 it was convenient to convert $\dot{V}O_2^{\mathrm{dem}}$ measured in oxygen equivalents per time to a metabolic rate (P_{met}) measured in energy per time. For the sake of consistency, this approach was used in both experiments.

I.A. Experiment 1

Seven male participants, all with experience in competitive skiing at a high national level, gave their written consent to participate in this study. They were asked to complete 8 sub-maximal loads à 5 minutes on a roller skiing treadmill (Rodby, Södertälje, Sweden) at skiing speeds $v = \{2, 3, 4, 5, 6, 7\}\,\mathrm{m{\cdot}s^{-1}}$. Each load was completed once using the V2 sub-technique. In addition, the $2\,\mathrm{m{\cdot}s^{-1}}$ and $7\,\mathrm{m{\cdot}s^{-1}}$ loads were repeated using the V1 and V2a sub-techniques, respectively. Treadmill inclination was set so that $P_{\mathrm{prop}} = 2.25\,\mathrm{W \cdot kg^{-1}}$ during all loads. All participants used the same pair of roller skis with C_{rr} 0.021, measured using a towing test. P_{met} was calculated from gas exchange measurements during the last minute of every load following the method proposed by Garby and Astrup [1]:

$$P_{\mathrm{met}} = \dot{V}O_2\,(A \cdot \mathrm{RER} + B)\,, \tag{1}$$

where $A = 4.940\,\mathrm{kJ{\cdot}}L^{-1}$, $B = 16.04\,\mathrm{kJ{\cdot}}L^{-1}$ and RER is the respiratory exchange ratio. Ordinary least squares regression was performed on the $v - P_{\mathrm{met}}$ relationship for each participant, excluding the $2\,\mathrm{m{\cdot}s^{-1}}$ and $7\,\mathrm{m{\cdot}s^{-1}}$ loads using the V2 sub-technique. The pooled regression residuals from all participants were checked for normality using a Shapiro-Wilk test.

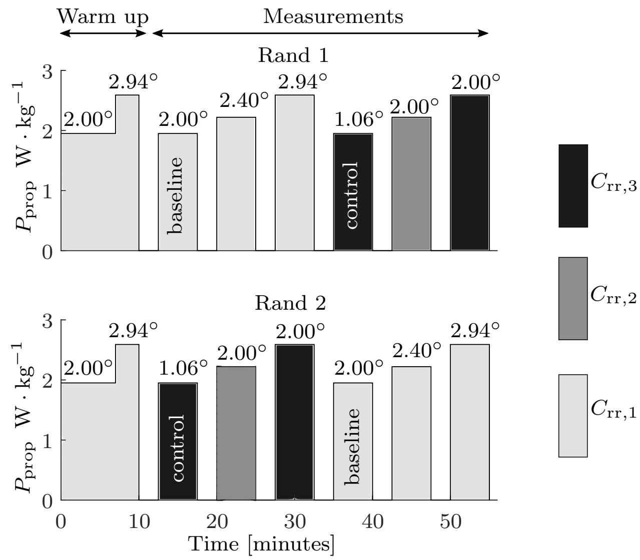

FIG. 1 Illustration of the protocol used to calculate delta efficiencies in experiment 2. The athletes were assigned to one of the two protocols (Rand 1 or Rand 2). Three pairs of roller skis with different C_{rr} ($C_{\mathrm{rr},1} < C_{\mathrm{rr},2} < C_{\mathrm{rr},3}$) were used.

I.B. Experiment 2

The protocol described here aimed at answering H.II using two different approaches. The first approach was to compare changes in $\dot{V}O_2^{\mathrm{dem}}$ when work against gravity or friction were increased by the same amount. The second approach was to compare $\dot{V}O_2^{\mathrm{dem}}$ between two loads where the total work was equal, but the work distribution between gravitational and frictional work was changed.

Participants: Seven athletes (6 males, 1 female) gave their written consent to participate in this experiment. All participants had experience in ski racing at national or international level.

Experimental protocol: Following a standardized 10 minute warm-up, the athletes completed 6 loads à 5 minutes. All loads were completed using the V2 technique at treadmill speed $v = 4.00\ \mathrm{m{\cdot}s^{-1}}$. The work done during each load was varied by changing C_{rr} or treadmill inclination (θ) following one of the two protocols shown in Figure 1.

Taking the first protocol (Rand 1) as a starting point, the first load (2°, $C_{\mathrm{rr}1}$) was defined as the baseline load. The fourth load (1.06°, $C_{\mathrm{rr}3}$), was designed to match the work of the baseline load, but the distribution of work against gravity and rolling resistance was different from the baseline load. Specifically, the fraction of work against rolling resistance to total work changed from 29 % during the baseline load to 62 % during the fourth load. This load was termed the control load (Figure 1).

Loads number [2, 5] and [3, 6] increased work by 14 %

and 33 % from the baseline load, respectively. However, this increase was achieved through increased treadmill inclination during loads 2-3 and increased rolling resistance during loads 5-6 (still assuming Rand 1, Figure 1).
Data analysis: P_{prop} was defined as the sum of work against gravity and rolling resistance divided by load duration. This was calculated from the expression commonly used during treadmill roller skiing:

$$P_{\text{prop}} = \dot{W}_{\text{gravity}} + \dot{W}_{\text{friction}} \tag{2}$$
$$= mgv\sin\theta + mgvC_{\text{rr}}\cos\theta, \tag{3}$$

where m is the mass of the athlete and equipment and $g = 9.82\,\text{m·s}^{-2}$ is the acceleration of gravity. C_{rr} was measured using a towing test with the treadmill in the horizontal position and $v = 4.00\,\text{m·s}^{-1}$. C_{rr} of roller skis is known to change with time and to depend on the normal force[2]. Therefore, the measurements of C_{rr} were repeated three times during the data collection to correct for drift in rolling resistance. In addition, C_{rr} was measured for both the lightest and one of the heaviest skiers to correct for deviations from nonlinearity of rolling resistance with the normal force. A linear regression model was used to estimate C_{rr} for each skier based on body mass and the time of the measurement. The linear regression model was:

$$C_{\text{rr}} = \beta_0 + \beta_1 \cdot t + \beta_2 \cdot F_{\perp}, \tag{4}$$

where C_{rr} was the measured coefficient of rolling resistance, t was the time of the measurements (counted in days), and $F_{\perp} = mg$ was the normal force. All measurements were completed using skis pre-heated to 60°C in a heated cabinet (Swix, Warmbox T007680-110, Lillehammer, Norway) to minimize the effects of wheel temperature changes on C_{rr}[2,3]. The C_{rr} values were $C_{\text{rr},1} = 0.0145 \pm 0.003$, $C_{\text{rr},2} = 0.0212 \pm 0.007$ and $C_{\text{rr},1} = 0.0302 \pm 0.008$ on average over all tests (mean ± SD) .

P_{met} was calculated from the gas exchange during the last minute of every load using the method described in experiment 1. Lastly, delta efficiencies were calculated using ordinary least squares regression with P_{prop} as predictor and P_{met} as the dependent variable:

$$P_{\text{met}} = \alpha_0 + \alpha_1 \cdot P_{\text{prop}}. \tag{5}$$

$\eta_{\Delta\text{gravity}}$ was defined as α_1^{-1} when the regression was done on loads 1, 2 and 3 (assuming rand 1). Correspondingly, $\eta_{\Delta\text{friction}}$ was defined as α_1^{-1} when the regression was done on loads 1, 5 and 6 (still assuming rand 1).
Statistics: This experiment allowed two testable hypotheses relating to H.II. The first hypothesis was that the delta efficiencies found when varying work against rolling resistance or gravity were equal, $\eta_{\Delta\text{friction}} = \eta_{\Delta\text{gravity}}$. The second hypothesis was that metabolic rate during the baseline and control loads were equal. Statistical inferences for these two hypothesis were made from paired t-tests on the delta efficiencies and metabolic rates, respectively. Results are presented in the text as mean ± standard deviation.

II. RESULTS

II.A. Experiment 1

Figure 3 shows that there was a linear relationship between skiing speed and P_{met} at constant P_{prop}. The slope of the regression line was $0.68 \pm 0.05\,\text{J·(m·kg)}^{-1}$, and the Shapiro-Wilk test failed to reject the hypothesis of normally distributed residuals (p=0.45). Further, there were no clear indications of heteroscedasticity in the residual plot (Figure 3B). However, the two loads using the V2 technique at $v = 2$ and $7\,\text{m·s}^{-1}$ tended to have a higher P_{met} compared to the loads at the same speeds using the V1 or V2a techniques (Figure 3B, marked ×).

II.B. Experiment 2

The results show that $\eta_{\Delta\text{gravity}}$ was significantly greater than $\eta_{\Delta\text{friction}}$ ($p < 0.001$), amounting to $21.7 \pm 2.9\,\%$ and $18.5 \pm 2.0\,\%$ on average, respectively. In contrast, P_{met} from the control load was not significantly different from the baseline load ($p = 0.96$). Figure 2 shows a scatter plot of the pairs of P_{met} and P_{prop} used to calculate delta efficiencies.

III. DISCUSSION

The results of experiment 1 show that during roller ski skating, P_{met} increases linearly with skiing speed when both inclination and speed are manipulated so that P_{prop} is unchanged. This is in agreement with H.I. However, when the athletes used sub-techniques outside of the speed range in which they are typically employed (i.e. V2 technique at 2 and 7 m·s^{-1}), P_{met} was elevated compared to the more common choices of V1 or V2a. Therefore, H.I only holds when skiers are free to select an appropriate sub-technique.

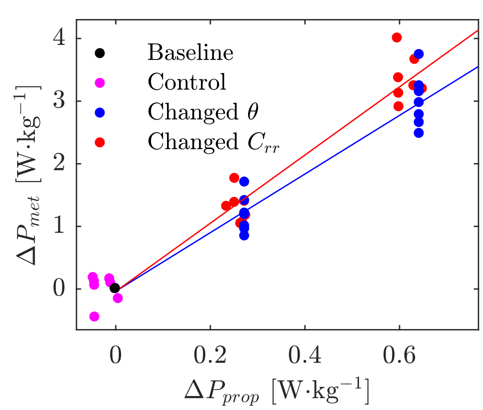

FIG. 2 Results from Experiment 2 showing how P_{met} changed from the baseline load ($\theta = 2°$, $C_{\text{rr}1}$) when work against rolling resistance (red dots) or gravity (blue dots) was increased. P_{met} increased more if additional work was done against rolling resistance rather than against gravity. Magenta dots are from the control load designed to match P_{prop} of the baseline load. P_{met} was not different between these two loads.

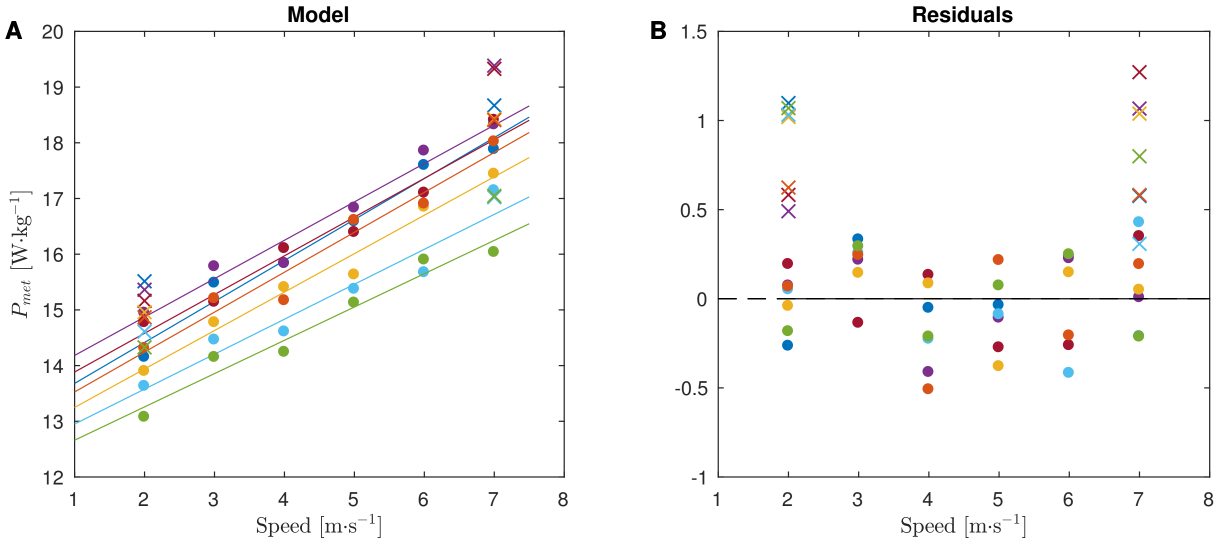

Fig. 3 (**A**) Scatter plot of skiing speed against steady-state metabolic rate. Each participant is represented by a unique color and the least squares regression lines are colored accordingly. The $\times$-symbols at 2 and 7 m·s^{-1} were omitted from the regression analysis because the athletes used the V2-technique, which is rarely applied at these speeds (see text for details). (**B**) Scatter plot of the regression residuals from panel (A). There were no clear indications of heteroscedasticity or other systematic effects.

The results from experiment 2 are conflicting. The finding that P_{met} was not different between the control and baseline loads supports H.II, but the finding that $\eta_{\Delta\text{friction}} \neq \eta_{\Delta\text{gravity}}$ opposes it. One possible explanation could be that the perturbation of work distribution between the baseline and control loads was insufficient to induce a measurable change in P_{met}. The appropriateness of this explanation can be assessed using the delta efficiencies to predict the change in P_{met} from baseline to control, which is given by $\Delta P_{\text{met}} = \Delta P \cdot ({\eta_{\Delta\text{gravity}}}^{-1} - {\eta_{\Delta\text{friction}}}^{-1})$. Here $\Delta P = 0.645\,\text{W}\cdot\text{kg}^{-1}$ was the increase (or decrease) in work against rolling resistance (or gravity) from the baseline to control load. This amounts to $\Delta P_{\text{met}} = 0.5 \pm 0.2\,\text{W}\cdot\text{kg}^{-1}$, which is substantially greater than the observed value of $0.0 \pm 0.2\,\text{W}\cdot\text{kg}^{-1}$. This indicates that the perturbation should have produced a measurable change in P_{met}, and therefore this explanation does not resolve the conflict.

The findings of experiment 2 affect the interpretation of experiment 1. Specifically, the finding of no difference in P_{met} between baseline and control loads (experiment 2) implies that P_{met} in experiment 1 should be unaffected by the varying work distribution between gravity and rolling resistance. This is true because all loads in experiment 1 were work-matched, similar to the control and baseline loads in experiment 2. Consequently, all of the variation in P_{met} during experiment 1 should be attributed to changes in skiing speed, which were not addressed in experiment 2. However, this interpretation is inappropriate in light of the finding that $\eta_{\Delta\text{gravity}} \neq \eta_{\Delta\text{friction}}$. In this case, part of the variation in P_{met} during experiment 1 can be directly attributed to changes in work against rolling resistance and gravity. We can calculate the expected change in P_{met} following changes in work against rolling resistance and gravity during experiment 1. These calculations (outlined in section V) show that when speed increases, P_{met} should increase by $0.16 \pm 0.05\,\text{J}\cdot(\text{m}\cdot\text{kg})^{-1}$ due to the increased work against rolling resistance and decreased work against gravity. This is small, but not negligible compared to the observed slope ($0.68 \pm 0.05\,\text{J}\cdot(\text{m}\cdot\text{kg})^{-1}$) during experiment 1. Consequently, most of the increase in P_{met} ($\approx 76\%$) is explained by changes in skiing speed. However, a small part of the increase ($\approx 24\%$) might be attributed to changes in the work distribution against rolling resistance and gravity.

The model for P_{met} (or $\dot{V}\text{O}_2^{\text{dem}}$) used in the current study does not account for the finding that $\eta_{\Delta\text{gravity}} \neq \eta_{\Delta\text{friction}}$. However, extending the model in the current study to be compatible with this finding is challenging for at least two reasons. First, the results in the current study include work against air drag. It would be experimentally challenging to determine the η_Δ for work against air drag. Second, there is no obvious way to include different η_Δ in the power-balance equation presented in Gløersen et al. [4]. The key point of this equation is that $P_{\text{prop}} = 0$ when the energy dissipated to the environment (i.e. air drag and rolling resistance) equals the rate of change in mechanical energy. Introducing different η_Δ for energy dissipation to the environment and changes in mechanical energy would violate this key point.

The findings in experiment 2 are strongly dependent on the measurements of work done against gravity and rolling resistance. Therefore, we performed some additional measurements to test the validity of these findings. As specified in the methods, C_{rr} was measured repeatedly and adjusted for differences in the athletes' weights. In addition, the model used for $\dot{W}_{\text{friction}}$ (Equation 3) is a simplification in at least three aspects: (*i*) the normal force is reduced to some extent by unloading through the ski poles, (*ii*) shear forces occur due to mediolateral oscillations of the center of mass and (*iii*) the roller skis do not move strictly parallel to the skiing direction. In addition, the calculation of $\dot{W}_{\text{gravity}}$ is dependent on accurate measurements of treadmill inclination. We assessed the effects of points (*i-iii*) for one of the participants using an optical motion capture system and ski poles with force transducers. This allowed us to calculate the average component of the pole forces normal to the treadmill, the magnitude of the mediolateral shear forces, and the true length of the skis' trajectories when in contact with the treadmill. In addition, we used the same motion capture system to check the accuracy of the treadmill's inclination. Although each of these points had some effect on the results, the combined effect did not change the conclusions.

IV. CONCLUSION

The model for $\dot{V}O_2^{\text{dem}}$ used in the current study is based on hypotheses H.I and H.II stated at the beginning of this appendix. The findings presented here support H.I, but are conflicting in answering H.II. However, the violation of H.II was shown to have only a minor effect on the prediction of P_{met}. We therefore conclude that the model in the current study is appropriate to answer the study's aims.

V. CALCULATIONS

This section describes how we calculated the expected change in P_{met} following changes in work distribution during experiment 1. We used the approximations $\sin\theta \approx \theta$ and $\cos\theta \approx 1$ (θ in radians), which simplified the calculations. The error of this approximation is $\leq 0.6\%$ for $\theta < 6°$. Under these approximations, P_{met} should be expected to follow the relationship

$$P_{\text{met}} = \frac{\dot{W}_{\text{gravity}}}{\eta_{\Delta\text{gravity}}} + \frac{\dot{W}_{\text{friction}}}{\eta_{\Delta\text{friction}}} + P_0, \tag{6}$$

$$= mgv\left(\frac{\theta}{\eta_{\Delta\text{gravity}}} + \frac{C_{\text{rr}}}{\eta_{\Delta\text{friction}}}\right) + P_0, \tag{7}$$

where $\dot{W}_{\text{gravity}}$ and $\dot{W}_{\text{friction}}$ are the work rates against gravity and rolling resistance, respectively, and P_0 represents the part of P_{met} that cannot be attributed to the work against gravity or rolling resistance. The behavior of P_0 is not important for the following arguments. It includes the baseline metabolic rate and all effects not directly connected to changes in work distribution, such as changes in skiing speed.

Both P_{prop} and C_{rr} were constant in experiment 1. In this situation, there is a unique relationship between θ and v:

$$\theta(v) = \frac{P_{\text{prop}}}{mgv} - C_{\text{rr}}. \tag{8}$$

This can be seen by rearranging Equation 3 and using the small angle approximation defined above. Substituting the expression for $\theta(v)$ into Equation 7 we find:

$$P_{\text{met}} = mgv\left(\frac{\frac{P_{\text{prop}}}{mgv} - C_{\text{rr}}}{\eta_{\Delta\text{gravity}}} + \frac{C_{\text{rr}}}{\eta_{\Delta\text{friction}}}\right) + P_0, \tag{9}$$

$$= C_{\text{rr}}mgv\left(\frac{1}{\eta_{\Delta\text{friction}}} - \frac{1}{\eta_{\Delta\text{gravity}}}\right) + \frac{P_{\text{prop}}}{\eta_{\Delta\text{gravity}}} + P_0, \tag{10}$$

In experiment 1 we assessed how P_{met} changed with speed at constant P_{prop}, i.e. $\partial P_{\text{met}}/\partial v|_{P_{\text{prop}}}$. Differentiating Equation 10 with respect to v gives us

$$\left.\frac{\partial P_{\text{met}}}{\partial v}\right|_{P_{\text{prop}}} = mgC_{\text{rr}}\left(\frac{1}{\eta_{\Delta\text{friction}}} - \frac{1}{\eta_{\Delta\text{gravity}}}\right) + \frac{\partial P_o}{\partial v}. \tag{11}$$

This first term of this equation is the change in P_{met} that can be attributed to $\eta_{\Delta\text{gravity}} \neq \eta_{\Delta\text{friction}}$. Putting in $C_{\text{rr}} = 0.021$ from experiment 1 and the values for $\eta_{\Delta\text{gravity}}$ and $\eta_{\Delta\text{friction}}$ from experiment 2, the expected increase in P_{met} due to changes in work distribution amounts to $0.16 \pm 0.05\,\text{J}\cdot(\text{m}\cdot\text{kg})^{-1}$. The last term in Equation 11 represents all effects of P_{met} that cannot be attributed to the different delta efficiencies. As discussed in section III, this appears to be the dominant term, and should be attributed to changes in skiing speed.

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