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The influence of slope and speed on locomotive power in cross-country skiing

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ABSTRACT

Purpose: A model was developed for cross-country skiing where locomotive power depends on speed and slope as variables, and further depends on snow friction, gravitation, mass, air drag, wind, and air density. Model parameters were estimated experimentally. *Methods:* Two differential equations were developed for how locomotive power depends on speed and slope. The equations are of the logistic form with a threshold determined by the skier's technique, intensity, mass, metabolic rate, gross efficiency, and lactate threshold. Three parameters were estimated by minimizing the average summed square difference between the simulated speed, using the model, and experimental speed of an elite male skier in a 4218 m track. Distance and height along the track were measured using a measuring wheel and an inclinometer generating 52 datapoints. Research assistants measured time from start at 14 different positions. Parameter values were determined from the literature. *Results:* We illustrated how speed and slope impact locomotive power. The model was shown to be superior to a model where locomotive power is a function of speed only. The joint dependence of locomotive power on speed and slope is crucial in the non-stationary conditions where the skier passes high and low points along the track where both speed and slope change rapidly. *Conclusion:* The model is useful to predict the impact of altering a subset of the 23 variables and parameters on the remaining variables, for example the impact of changed friction or terrain slope on the skier's speed and thus time to complete a ski race.

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1. Introduction

The two purposes of this paper were to develop a model of locomotive power in cross-country skiing, and estimate parameters in the model by using an experiment to illustrate the model's applicability. The three terms locomotive power, work rate, and mechanical power have been used interchangeably in the literature (de Koning & van Ingen Schenau, 1994; Moxnes, Sandbakk, & Hausken, 2014; Sandbakk, Ettema, & Holmberg, 2012; Sandbakk, Holmberg, Leirdal, & Ettema, 2010). In this paper we preferred to use the term locomotive power defined exclusively as power generating locomotion, i.e. power propelling the skier forward, thus excluding e.g. the resting metabolic rate or power. We modeled the skier's locomotive power to depend on five main factors, i.e. the terrain's slope, speed, technique, intensity, and mass. A skier's maximum locomotive power depends on his maximum and mean metabolic rate (Sandbakk et al., 2010, 2012; Sandbakk, Ettema, Leirdal, Jakobsen, & Holmerg, 2011), gross efficiency, and lactate threshold. Whereas slope and mass are given, speed, technique, and intensity further depend on air drag, wind, gravitation, air density, and friction (Bergh & Forsberg, 1992; Sandbakk et al., 2012; Smith, 1992) which in turn depends on snow quality, temperature, and mass.

The importance of power production in skiing is underscored by cross-country skiing invoking all major muscle groups which burn calories excessively. Ski legend Bjørn Dæhlie recorded a VO_2max of 96 ml/kg/min (World Best VO_2 max Scores, 2014). In the research on power production, de Koning, Bobbert, and Foster (1999) used an energy flow model to determine pacing in cycling, de Koning and van Ingen Schenau (1994) estimated mechanical power in endurance sports, and van Ingen Schenau and Cavanagh (1990) formulated Newtonian mechanics power equations for various endurance sports. For cross-country skiing, Carlsson, Tinnsten, and Ainegren (2011) simulated skiing numerically accounting for a variety of forces, and wind and glide situations, Moxnes and Hausken (2008), Moxnes, Sandbakk, and Hausken (2013) and Moxnes et al. (2014) developed motion equations, Sandbakk et al. (2011) analyzed time trials in different terrain sections while considering work rate and relationships to physiological and kinematic parameters while treadmill roller ski skating, and Sundstrøm, Carlsson, Ståhl, and Tinnsten (2013) optimized pacing strategy in skiing numerically applying skiing motion equations. References Moxnes et al. (2013), Norman and Komi (1987) and Sandbakk et al. (2012) found that locomotive power is high in uphill terrain. References Andersson et al. (2010) and Sandbakk et al. (2011, 2012) found that locomotive power decreases marginally as speed increases from zero towards 6 m/s, and decreases as speeds increase towards 10 m/s. For speeds above 10 m/s skiers usually use techniques such as the tuck position to save energy (Andersson et al., 2010). Using these insights locomotive power has recently been analyzed as a function of speed only (Moxnes et al., 2014; Sundstrøm et al., 2013).

This paper's contribution is to endogenize locomotive power more thoroughly into power production, in the sense of making locomotive power a variable in the model instead of an exogenously given parameter. Two differential equations were determined for how locomotive power depends on the skier's speed and the terrain's slope, additionally accounting for technique, intensity, and mass. The endogenized role of locomotive power was analyzed together with friction, gravitation, and air drag. Parameters in the model were estimated with an experiment.

2. Methods

2.1. Theoretical model development

A skier's locomotive power P depends complexly on many factors. We here focus on the five main factors, i.e. the terrain's slope $\alpha = \alpha(t)$, speed $v = v(t)$, technique $\alpha = \alpha(t)$, intensity $\varepsilon = \varepsilon(t)$, and the skier's mass m. The slope α is measured in radians between a tangent of the track and the horizontal level. In sufficiently steep downhill terrain, with negative α, locomotive power $P = P(v, \alpha, \varepsilon, \chi, m)$ is zero since the skier's legs and arms cannot keep up with the high speed and no locomotion is generated beyond the locomotion generated by gravity (subtracting friction and air drag). As the slope α increases to moderate downhill, legs and arms can generate some locomotion and locomotive power