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Full Length Article

The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers

Jørgen Danielsen*, Øyvind Sandbakk, David McGhie, Gertjan Ettema

Center for Elite Sports Research, Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway

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ABSTRACT

The purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in ergometer double poling (DP), while taking specific dynamic constraints into account. One main question was whether lower-body power contribution increased or decreased with increasing intensity. Nine male Norwegian national-level cross-country skiers performed ergometer DP at low, moderate, high and maximal intensity. Kinematics, and ground (GRF) and poling (F_{poling}) reaction forces were recorded and used in link segment modeling to obtain joint and whole-body dynamics. Joint powers were averaged over the cycle, the poling (PP) and recovery (RP) phases. The contribution of these average powers was their ratios to cycle average poling power. At all intensities, the shoulder (in PP) and hip (mostly in RP) generated most power. Averaged over the cycle, lower-body contribution (sum of ankle, knee and hip power) increased from ~37% at low to ~54% at maximal intensity ($p < .001$), originating mostly from increased hip contribution within PP, not RP. The generation of larger F_{poling} at higher intensities demanded a reversal of hip and knee moment. This was necessary to appropriately direct the GRF vector as required to balance the moment about center of mass generated by F_{poling} (control of angular momentum). This was reflected in that the hip changed from mostly absorbing to generating power in PP at lower and higher intensities, respectively. Our data indicate that power-transfer rather than stretch-shortening mechanisms may occur in/between the shoulder and elbow during PP. For the lower extremities, stretch-shortening mechanisms may occur in hip, knee and trunk extensors, ensuring energy conservation or force potentiation during the countermovement-like transition from body lowering to heightening. In DP locomotion, increasing intensity and power output is achieved by increased lower-body contribution. This is, at least in ergometer DP, partly due to changes in joint dynamics in how to handle dynamic constraints at different intensities.

1. Introduction

In most cross-country (XC) skiing techniques, forward motion is made possible by generation of propulsive forces applied to the ground by the skier through the poles and skis. As such, transformation of power generated by muscle to external power and speed relies on coordinated interaction between the joints and segments of both the upper and lower body (e.g., Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005; Lindinger, Holmberg, Müller, & Rapp, 2009; Lindinger, Stöggl, Müller, & Holmberg, 2009). Double

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* Corresponding author at: Department of Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology, 7489 Trondheim, Norway.

E-mail address: jorgen.danielsen@ntnu.no (J. Danielsen).

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poling (DP), one of the main classical style XC skiing techniques, is the only technique in which propulsive forces are applied solely through the poles. This is because in DP the skis continuously glide, whereby only motion-resisting friction forces occur between skis and surface and it is not possible to produce thrust in the forward direction. The same principle applies to DP on an ergometer (e.g., the Concept2 SkiErg frequently used in XC ski training): although the athlete stands on a full friction surface (ground), external poling power (P_{poling}) is finally produced through a set of ropes resisted by an external device (see e.g., Danielsen, Sandbakk, Holmberg, & Ettema, 2015). Therefore, upper body work is accentuated in DP (e.g., Dahl, Sandbakk, Danielsen, & Ettema, 2017; Danielsen et al., 2015; Holmberg et al., 2005). Still, via a transfer of body mechanical energy (E_{body}), P_{poling} can to a large extent originate from energy generated by lower body muscles (see Danielsen et al., 2015).

We previously showed that, in ergometer DP, work done by the extending lower body is mainly done in the recovery phase (RP), which increases E_{body} (Danielsen et al., 2015). As the center of mass (CoM) is lowered and the body rotated forward in the following poling phase (PP), part of this E_{body} is transferred to external ergometer work (i.e., one 'falls' on the ropes). It was estimated that ~66% and ~53% of net muscle work over the movement cycle was done in the RP at low and maximal intensity, respectively, presumably by lower body muscles. Accordingly, the remainder should originate from upper body work, which directly leads to P_{poling}.

The estimation that more than 50% of net muscle work was done by the lower body was based on the assumption that the PP and RP separate work done by the upper and lower body, respectively. However, this amount did not increase but rather decreased when intensity increased, which is in disagreement with e.g., Bojsen-Møller et al. (2010), Rud, Secher, Nilsson, Smith, and Hallén (2014) and Zoppirolli et al. (2016). They found that increasing both ergometer and skiing DP intensity relied more upon increased lower than upper body involvement. Of course, the assumption made in the previous investigation (Danielsen et al., 2015) might not be correct; the amount of work done by the upper and lower body does not necessarily correspond to the poling-recovery division. For example, repositioning of the body through trunk, hip, and knee extension start slightly before the end of PP (Danielsen et al., 2015; Holmberg et al., 2005).

In Danielsen et al. (2015) it was also assumed that most of the decreasing E_{body} during PP was used directly for propulsion. However, at the start of PP a small but significant part was absorbed by muscles, most likely in the lower extremity. This raised the question of whether lower body muscle-tendons store and reutilize mechanical energy in stretch-shortening cycles (SSC) in the countermovement-like action that is the immediate transition from body lowering to heightening. An inverse dynamics analysis is needed to elucidate these issues.

An analysis of dynamics may also shed light on an often overlooked issue in DP, which is the need to control changes in body angular momentum by appropriately balancing the net moment about the CoM. The generation of oblique poling forces (F_{poling}) poses specific requirements on the moment about CoM generated by the ground reaction force (GRF) of the lower extremity, which must counteract the moment generated by F_{poling}. This dynamic constraint demands specific joint moments and powers generated by appropriate coordination, which may be affected by intensity.

Accordingly, the main purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in ergometer DP. In particular, we re-examined the relationship between lower-body power contribution and DP intensity. We hypothesized that, given our earlier findings (Danielsen et al., 2015), in case the relationship is positive it should coincide with considerable work done by the lower body during PP. Moreover, taking specific dynamic constraints into account, we aimed to further our understanding of DP energetics and dynamics with regard to joint power generation, absorption and possible transfer.

2. Methods

The experimental procedures and data of the present paper originate partly from a previous study (Danielsen et al., 2015), where the main purpose was to examine fluctuations in body mechanical energy in relation to external ergometer work as well as to estimate instantaneous net muscle-tendon work rate.

2.1. Participants

Nine male Norwegian national level XC skiers (age 24 ± 5 yrs, height 1.86 ± 0.06 m, body mass 81.7 ± 6.5 kg, VO_{2peak} running 73 ± 6 ml·kg·min^{-1}) voluntarily participated in this study. Before providing written informed consent, the participants were verbally informed about the nature of the study and their right to withdraw at any point was explicitly stated. Permission to conduct the study was given by the Regional Committee for Medical and Health Research Ethics in Central Norway, and the study was registered at Norwegian Science Data Services.

2.2. Experimental design

Following a 15-min warm-up of low intensity running on a treadmill and ergometer DP, the participants performed three 4-min submaximal trials of DP at low (LOW), moderate (MOD), and high (HIGH) intensity levels, with 1–2 min rest between the trials. After an active recovery period of ~5 min the participants completed one 3-min closed-end performance test (MAX). During each trial, kinetics and kinematics were collected after steady-state external power production had been achieved.

DP was performed on a Concept2 SkiErg (Concept2 Inc., Morrisville, VT, USA) mounted to the wall. The aero-resistance of the ergometer was set at the lowest level to minimize poling times, thereby best mimicking skiing DP (Halonen et al., 2015). The advantage of using ergometer DP as a model is that the definition of instantaneous external power is unambiguous (as opposed to ski