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Skiing efficiency versus performance in double-poling ergometry

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This is a study on how leg utilization may affect skiing efficiency and performance in double-poling ergometry. Three experiments were performed, each with a different style of the double-poling technique: traditional with small knee range-of-motion and fixed heels (TRAD); modern with large knee range-of-motion and fixed heels (MOD1); and modern with large knee range-of-motion and free heels (MOD2). For each style, motion data was extracted with automatic marker recognition of reflective markers and applied to a 3D full-body musculoskeletal simulation model. Skiing efficiency (skiing work divided by metabolic muscle work) and performance (forward impulse) were computed from the simulation output. Skiing efficiency was 4.5, 4.1 and 4.1% for TRAD, MOD1 and MOD2 respectively. Performance was 111, 143 and 149 Ns for TRAD, MOD1 and MOD2 respectively. Thus, higher lower-body utilization increased performance but decreased skiing efficiency. This result demonstrates the potential of musculoskeletal simulations for skiing efficiency estimations.

Keywords: AnyBody Modeling System; AviMes AD; biomechanics; cross-country skiing; impulse; musculoskeletal simulation

1. Introduction

An early attempt to clarify the problem of the efficiency of human movement was made by Cavanagh and Kram (1985). They pointed out that there are a number of different factors (biomechanical, physiological, biochemical etc.) that influence overall energy cost for a given movement and that there is also confusion about terminology regarding movement efficiency. Recently, Winter and Fowler (2009) concluded that conflicting "exercise measures" and confusing terminology are still common. In contrast to the experimental methods discussed by Cavanagh and Kram (1985) and Winter and Fowler (2009), a mathematical model of the human body makes it possible to be more clear and concise when defining energy cost and efficiency, thus avoiding confusion.

In a series of papers, Norman and co-workers estimated the energy cost of diagonal skiing by using a mathematical model to compute the internal work by segment analysis (Norman et al. 1985; Norman and Komi 1987; Norman et al. 1989). Generally, they found large individual differences even among elite skiers.

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Figure 1. Photo of skier performing MOD2 style on double-pole ergometer.

Whether this was due to movement skill differences between skiers or inaccuracies within the method is not clear. The authors pointed out that it would be ideal to use the dot product of muscle force and velocity to estimate muscle power and subsequent energy cost, but that was beyond the state-of-art. Later, Sasaki et al. (2009) compared different mathematical models for estimating muscle work during walking. They found that computing internal work by segment analysis yields $\sim 40\%$ less work than work computed using a musculoskeletal model. None of the classical methods (e.g. external, internal or joint work), albeit clear and concise, performed well. Sasaki et al. (2009) concluded that a musculoskeletal model is best suited for estimating the amount of muscle work required for different movements.

Contemporary elite skiers utilize their legs a lot more when double-pole than two decades ago. Whether this is good for skiing efficiency and/or performance is not fully known, nor has it previously been estimated with a mathematical model.

The aims of this project were: 1) to study whether differences in leg utilization during double-pole ergometry affect skiing efficiency and performance; and 2) to study the potential of musculoskeletal simulations for estimating skiing efficiency.

2. Methods

One trained male skier performed three 30 s experiments on a double-pole ergometer¹, see Figure 1. The air-friction-braked flywheel on the ergometer was kept at the same setting throughout. The skier was told to maximize his effort and use a different style of double-pole in each experiment. The TRAD style was characterized by a small range-of-motion of the knee and ankle joints together with a heel fixed to the ground. The MOD1 style was characterized by a large range-of-motion of the knee joint but a small range-of-motion for the ankle joint together with a fixed heel. The MOD2 style had a large range-of-motion of both knee and ankle joints together with a free heel (such that the skier got up on his forefoot prior to pole plant). Thus, TRAD showed a strong similarity to traditional double-pole. In contrast, both MOD1 and MOD2 showed similarities to modern double-pole, utilizing the legs much more than TRAD. For each style, motion

¹A modified Concept II C, Concept Inc., Morrisville, VT, USA

data was extracted² at 50 Hz for one complete and representative cycle (after steady state occurrence) and then implemented in a 3D full-body musculoskeletal model³. Altogether, three different simulation models, each one with unique kinematics and kinetics, but with exactly the same body anthropometrics, performing the same task (double-poling ergometry at maximum effort) at similar frequency. With these models it is possible to pinpoint the influence of lower-body kinematics (i.e. leg utilization) by the following calculations (all based on simulation output).

Useful skiing work output, w^{skiing} , is defined as,

$$w^{\text{skiing}} = 2 \int_0^{PT} f_x^{\text{pole}} v_x^{\text{poletip}} dt \quad (1)$$

where PT is the time of the poling-phase, defined as the time when the pole tips are moving backwards on the ergometer (pole tips are moving forward during the return-phase); f_x^{pole} is the horizontal component of the force exerted by the pole; v_x^{poletip} is the horizontal velocity of the pole tip and two poles yield the factor 2.

Mechanical muscle power, p_i^{muscle} for each muscle $i = 1, \dots, n$ where n is the number of muscles, is defined as the dot product of muscle force and velocity,

$$p_i^{\text{muscle}} = f_i^{\text{muscle}} v_i^{\text{muscle}} \quad (2)$$

where $f_i^{\text{muscle}} > 0$ and it is the force in the i^{th} muscle and v_i^{muscle} is the corresponding shortening or lengthening muscle velocity (one-dimensional).

Beltman et al. (2004) showed that energy cost were lower for a lengthening muscle than for a shortening muscle. Hence, as a crude estimation, metabolic muscle power, $p_i^{\text{met muscle}}$, is defined as,

$$p_i^{\text{met muscle}} = \begin{cases} p_i^{\text{muscle}}/0.25 & \text{if } p_i^{\text{muscle}} > 0 \\ -p_i^{\text{muscle}}/1.25 & \text{if } p_i^{\text{muscle}} < 0 \end{cases} \quad (3)$$

The metabolic muscle work, $w_i^{\text{met muscle}}$, can now be computed as,

$$w_i^{\text{met muscle}} = \int_0^{CT} p_i^{\text{met muscle}} dt \quad (4)$$

where CT is the time of one complete double-poling cycle. This was also computed separately for the poling-phase by adjusting the integration upper limit to PT . Total metabolic muscle work for the whole body, $w^{\text{met total}}$, is,

$$w^{\text{met total}} = \sum_{i=1}^n w_i^{\text{met muscle}} \quad (5)$$

where n is the number of muscles. (5) represent the energy cost of the movement. This was also computed separately for lower- and upper-body. The lower-body is defined as comprising all muscles in the model that has at least one attachment point distal of the hip joint.

Skiing efficiency, η^{skiing} , can now be computed using (1) and (5),

$$\eta^{\text{skiing}} = \frac{w^{\text{skiing}}}{w^{\text{met total}}} \quad (6)$$

²Using automatic marker recognition of reflective markers in AviMes AD 2.4, ISC Matej Supej s.p., Kranjska Gora, Slovenia

³The AnyBody Modeling System™3.0, AnyBody Technology A/S, Aalborg, Denmark

Table 1. Simulation data.

MEASURE (units)	TRAD	MOD1	MOD2
Cycle time (s)	1.4	1.3	1.4
Relative poling-phase (%)	50	52	46
Time to peak pole force, axial ^a (s)	0.34	0.32	0.26
Peak pole force, axial ^a (N)	171	217	235
Time to peak pole force, forward ^b (s)	0.34	0.35	0.29
Peak pole force, forward ^b (N)	147	185	196
Heel lift angle range-of-motion ^c (°)	-	-	27
Ankle joint range-of-motion ^d (°)	13	12	39
Knee joint range-of-motion ^d (°)	13	48	50
Hip joint range-of-motion ^d (°)	81	97	94
Elbow joint range-of-motion ^d (°)	62	59	60

^aIn the longitudinal (axial) direction of the pole.

^bHorizontal component, and thus the forward propulsive force.

^cAngle between ground and an approximate axis from the metatarsophalangeal joint to the distal part of calcaneus (ball to heel).

^dFlexion/Extension angle.

Skiing performance, imp_x^{skiing} , is defined as the horizontal impulse generated by the two poles,

$$imp_x^{\text{skiing}} = 2 \int_0^{PT} f_x^{\text{pole}} dt \quad . \quad (7)$$

Except for motion data extraction enhancements, experimental and simulation procedures were carried out as described in detail by Holmberg and Lund (2008).

3. Results

All presented results are simulation output. See Table 1 and Figure 2¹, for the kinematic and kinetic differences between the three double-poling styles.

Cycle times (and thus frequency) were similar for all three styles. There were great differences in the ranges-of-motion of the knee and hip between TRAD and the other styles. The main differences between MOD1 and MOD2 were heel lift and range-of-motion of the ankle. For upper-body joints, there were only minor differences between the three styles (see Table 1 and Figure 3). Pole inclination was consistently lower for MOD2 than for the other styles during the poling-phase (Figure 4(a)). Peak pole force was higher for MOD2 than for MOD1 which in turn was considerably higher than for TRAD (Figure 4(b)). Time to peak pole force was shorter for MOD2 than for the others. Altogether, the differences in pole inclination and pole force yield a higher impulse in the forward direction for MOD2 compared with the other styles.

TRAD has the greatest skiing efficiency (6), while MOD2 yields the highest performance (7), see Table 2. For MOD2, lower-body muscles do most of the total metabolic muscle work (5). For TRAD and MOD1, metabolic muscle work is distributed relatively even between upper- and lower-body (Table 2).

¹See also the supplementary online material, som1.mpg and som2.mpg (slow motion)

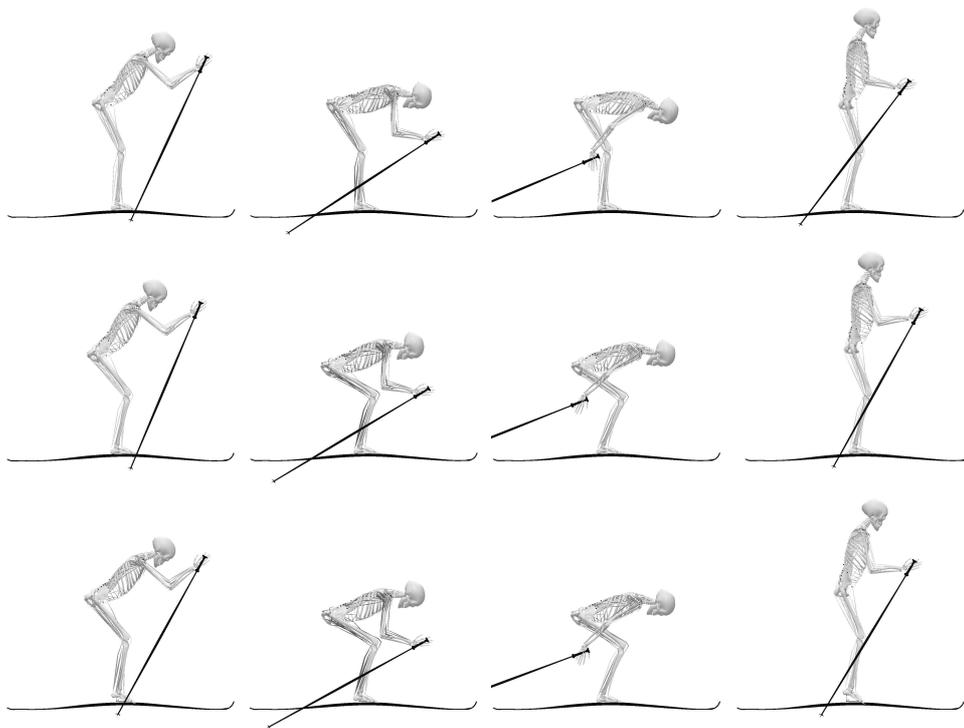


Figure 2. Visual overview of simulation kinematics and muscle activity. Rows: 1) TRAD 2) MOD1 3) MOD2. Columns: 1) Beginning of poling-phase (~ 0.1 s) 2) Max pole force (~ 0.3 s) 3) End of poling-phase (~ 0.6 s) 4) End of return-phase (~ 1.2 s) (times are from the beginning of a cycle).

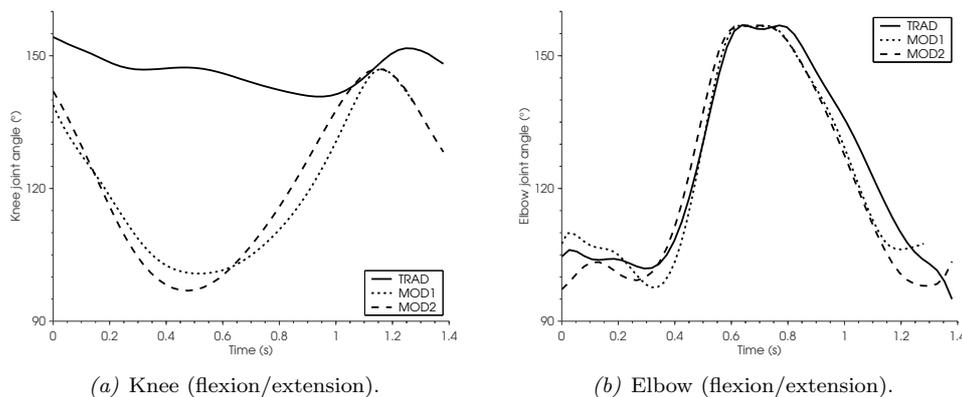
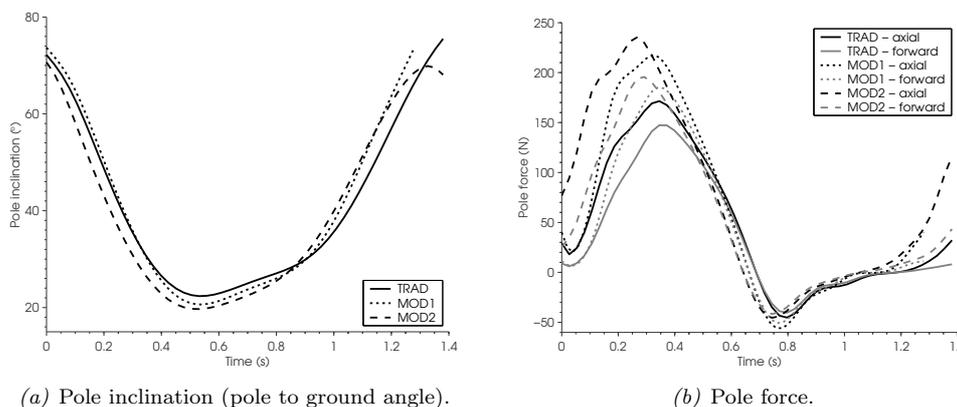


Figure 3. Simulation joint angle data for the knee and elbow.

4. Discussion

The main findings were: 1) differences in leg utilization have an effect on skiing efficiency and performance, but performance does not necessarily correspond to skiing efficiency, because in this study the style with the highest performance is also the one with lowest skiing efficiency; and 2) the method shown has great potential for efficiency studies in cross-country skiing.

Skiing work, impulse and energy cost (total and during the poling-phase) are considerably higher for MOD2 and MOD1 than for TRAD (Table 2). For MOD1, this extra energy cost is rather evenly distributed between the lower- and upper-body, while for MOD2 it is the lower-body that does most of the extra work. There is a high energy cost associated with "getting back into position" for MOD2 (com-



(a) Pole inclination (pole to ground angle).

(b) Pole force.

Figure 4. Simulation pole data. The negative forces in the beginning of the return-phase and the positive forces at the end of the return-phase are an artefact of ergometer double-poling.

Table 2. Skiing efficiency versus performance^a.

MEASURE (units)	TRAD	MOD1	MOD2
Skiing work (Nm)	111	141 ^b	146
Metabolic muscle work, total (Nm)	2479	3463 ^b	3589
Skiing efficiency (%)	4.5	4.1	4.1
Skiing performance (impulse ^c) (Ns)	111	143 ^b	149
Metabolic muscle work, lower-body (Nm)	1207	1646 ^b	1992
Metabolic muscle work, lower-body (%)	49	48	55
Metabolic muscle work, upper-body (Nm)	1272	1817 ^b	1597
Metabolic muscle work, upper-body (%)	51	52	45
Metabolic muscle work, return-phase (Nm)	1038	1353	1645
Metabolic muscle work, poling-phase (Nm)	1441	1863	1944
Return/poling ratio ^d (%)	72	73	85

^aUnless stated otherwise, values are for one complete double-poling cycle (defined as the phase from pole plant to the subsequent pole plant).

^bValue adjusted by 14/13 to compensate for the shorter cycle time (higher frequency) of MOD1, see Table 1.

^cIn the forward direction (i.e. not axially through the pole).

^dThe ratio of metabolic muscle work between return- and poling-phase.

pare the return/poling ratios in Table 2). Despite this, it seems that heel-lifting is beneficial because the skiing efficiency of MOD2 and MOD1 is equal, but performance is higher for MOD2. Excessive knee-bending is apparently not beneficial for skiing efficiency, because TRAD has the highest skiing efficiency. Holmberg et al. (2006), Lindinger et al. (2009) and Lindinger and Holmberg (2011) studied elite skiers who performed double-poling on a treadmill at different velocities. Holmberg et al. (2006) found that completely restraining knee and ankle joint rotation impaired performance (impulse). Lindinger et al. (2009) found that lower-body joint velocities and range-of-motion increased when skiing velocity and pole force increased, implying higher performance (impulse) with higher leg utilization. However, they suggest that the more accentuated up-and-down movement at higher velocities probably consumes more energy. Lindinger and Holmberg (2011) showed that, for lower-body joints, "gross efficiency" was lower when the range-of-motion was higher. Altogether, these studies (Holmberg et al. 2006; Lindinger et al. 2009; Lindinger and Holmberg 2011) seem to support our results. Modern double-poling emerged due to the new sprint and mass start events, which demand higher speed capabilities from the skiers. The kinematics of modern double-poling, with heel-lifting, facilitates faster skiing by involving more muscles in forward locomotion. Moreover, at poling frequencies higher than those studied here, it may not be pos-

sible for the upper-body muscles to produce the necessary power needed with a traditional style of double-poling. In elite skiing, speed may sometimes be favoured over efficiency. Contrarily, in long-distance races, even elite skiers normally chose a more traditional double-poling style, except for sections with higher speeds and in the last sprint at the finish. It is important to realise that being able to generate high peak pole forces or locomotive power does not automatically imply a high level of skiing efficiency; spending the least possible amount of energy also matters.

We believe that the method shown here reveals that musculoskeletal simulations have great potential for efficiency studies in cross-country skiing. Although a real experiment served as a base, this is primarily a theoretical simulation study, and the results should not be generalized to on-snow skiing without noting that in double-poling ergometry, pulling the slide wagon demands substantial metabolic muscle work during the return-phase (see Table 2) that does not directly contribute to the locomotive work (see Equation 1). Even though double-poling ergometer performance has been shown to relate to on-snow double-poling performance (Holmberg and Nilsson 2008), additional demands when on-snow skiing are to minimizing friction and aerodynamic drag (Moxnes and Hausken 2009). Another possible source of uncertainty is the lack of muscle dynamics in the muscle model. Nevertheless, we would like to stress the fact that a detailed mathematical musculoskeletal model (as the one in this study) makes it possible to pinpoint the influence of slight changes in kinematics and kinetics, thus furthering the understanding of different movements. As far as we know, this has never previously been reported for cross-country skiing.

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