The Effect of Intensity on Joint-Specific Power and Mechanical Energy during Double Poling in Elite Cross-Country Skiers

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Master thesis
BEV3901
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2013/14

Abstract

Purpose. The present study examined the absolute behavior and the relative contributions to poling power of 1) joint-specific powers and 2) total body power (P_{body}, i.e. the rate of change in total body mechanical energy) at increasing intensities while ergometer double poling.

Methods. Nine male elite skiers (body mass 81.7 ± 6.5 kg, height 1.86 ± 0.06 m) performed three 4-min submaximal trials at low (LOW), moderate (MOD), and high (HIGH) intensity, and one 3-min all-out peak test (MAX). All trials were performed standing on a force plate and the ergometer was equipped with a force cell in order measure all external forces acting on the body. Reflective markers were placed on anatomical landmarks. Kinetics and kinematics were synchronized and recorded. By applying inverse dynamics, joint-specific powers (elbow, shoulder, trunk, hip, knee and ankle) and P_{body} was calculated for the poling and retrieval phase, and for the complete cycle.

Results. As net cycle poling power increased (116 ±16 W. 166 ± 36 W, 214 ± 38 W, and 306 ± 38 W at LOW, MOD, HIGH, and MAX, respectively; all $p < 0.05$) the relative contribution of the lower extremities increased from 39 ± 14 % at LOW to 65 ± 11 % at MAX ($p < 0.05$). The relative contribution of the upper extremities was stable at ~28 ± 6 %. Pbody fluctuated over the cycle, being generated during the retrieval phase (~100% of lower extremities positive power) and partly transferred to poling power during the poling phase. More specifically, P_{body} was the main contributor to poling power (66 ± 13 % at LOW and 54 ± 7 % at MAX). Overall, most power was produced by the body's core, i.e. the hip, trunk, and shoulder joints.

Conclusion.

The lower extremities generate an increasing amount of P_{body} during the retrieval phase, which was thereafter partly transferred to poling power during the poling phase. Enhancing the lower extremities' work as a way of increasing P_{body} during the retrieval phase seems crucial for optimal utilization of P_{body} during poling phase.

Key words: double poling, biomechanics, inverse dynamics, energy, cross-country skiing

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Introduction

In cross-country (XC) skiing propulsive forces are generated by a combination of upper body poling (through the poles) and lower body leg push-off (through the skis). The distribution of these forces differs significantly depending on the various techniques skiers employ during a single race (Sandbakk & Holmberg, 2014). Although double poling (DP) is the only technique in which all propulsive forces are generated through the poles, dynamic leg work is of great importance in suppressing physiological responses and increasing efficiency and performance (Holmberg, Lindinger, Stöggl, Björklund & Müller, 2006; van Hall et al., 2003). Studies also found a characteristic DP technique shift from the traditional (in use today by slower skiers) to the modern (in use today by faster skiers) technique, where especially the lower body is more involved in the latter (Holmberg, Lindinger, Stöggl, Eitzlmair & Müller, 2005). In fact, as intensity increases in modern DP, the lower body is responsible for the main increase in metabolic work (Rud, Secher, Nilsson, Smith & Hallén, 2013). Although it is known that dynamic upper and lower body work are important for optimal DP performance, the specific role and relative contributions from the various upper and lower body segments within different DP cycle phases remains unknown and requires further investigation.

One DP cycle can be divided into a poling phase (PPh) (i.e. pole ground contact), and a retrieval phase (RPh) (i.e. no pole ground contact), where all propulsive forces are generated during the PPh. The rationale is that, as intensity and subsequently lower body work is enhanced, the amplitude of the vertical movement of the total body center of mass ($CoM_{(t)}$) increases due to the “high hip – high heel” movement (see Holmberg et al., 2005). In the subsequent PPh, one, therefore, takes greater advantage of gravity by a forward rotation and active lowering of $CoM_{(t)}$. More external load is transferred to the poles and higher pole forces are produced during a short and dynamic PPh, which leads to a longer relative RPh. Thus, one achieves longer cycle lengths (CL) at lower cycle rates (CR) (Lindinger & Holmberg, 2011; Lindinger, Stöggl, Müller & Holmberg, 2009b). The latter is important for performance and efficiency also in other skiing techniques (Leirdal, Sandbakk & Ettema, 2013; Sandbakk, Holmberg, Leirdal & Ettema, 2010).

Because of the repetitive heightening and lowering of $CoM_{(t)}$, total mechanical energy of all body segments (E_{body}) is expected to be generated and absorbed over the DP cycle, as in for example running and jumping (Cavagna, Thus & Zamboni, 1976; van Soest, Schwab, Bobbert & van Ingen Schenau, 1993). In running, E_{body} is generated during ground push-off and absorbed during landing (Cavagna et al., 1976). Therefore, the net gain in E_{body} is zero (van Ingen Schenau, G. J., Bobbert & de Haan, 1997a). In DP, however, propulsion is generated by the body acting on the external force at the poles. Therefore, some of the E_{body} is likely transferred through the poles during ground contact, while some of the E_{body} is likely still absorbed by the joints, as in running (Elftman, 1940). By calculating the individual joint-specific powers, as well as the rate of change in E_{body} (P_{body}) in DP, one can investigate the relative contributions of these joint-specific powers and P_{body} to P_{poling}. Such an investigation requires the movement to be studied with a mechanical approach, such as the inverse dynamics analysis (Elftman, 1939). For inverse dynamics analysis, DP on an ergometer is well suited since one can easily define the body as a closed mechanical system. Additionally, ergometer DP has similar biomechanical and kinematic characteristics as skiing DP (Linnamo et al., 2013) and is frequently used by skiers in training. To the best of the author's knowledge, inverse dynamics analysis has not yet been performed on whole-body DP.

Therefore, the purpose of the present study was to investigate the effect of increasing intensity on the absolute and relative contributions of joint-specific powers and E_{body} to P_{poling} within the different phases of the DP cycle. It was hypothesized that the lower extremity power and E_{body} would increase its relative contribution as intensity increased.

Methods

Participants

Nine well-trained male XC skiers (age 24 ± 5 yrs, height 1.86 ± 0.06 m, body mass 81.7 ± 6.5 kg) volunteered to participate in this study. Before giving their written informed consent, all participants were verbally informed about the full nature of the study, and explicitly told that they could withdraw at any point without stating a reason. The study's experimental protocol was pre-approved by the Regional Ethics Committee, Trondheim, Norway.

Experimental protocol

After a 10-min low-intensity warm-up whilst running on a treadmill and a 5-min DP equipment familiarization all subjects performed: 1) three 4-min submaximal trials at low (LOW), moderate (MOD), and high (HIGH) intensity and 2) one 3-min closed-end performance test (MAX). A 1- to 2-min break separated the submaximal trials, while a 5-min active recovery period separated HIGH and MAX in order to avoid fatigue. Physiological, kinetic and kinematic variables were collected during all trials. In order to define the skier as a closed mechanical system, all trials were performed standing on a force plate, and the DP ergometer was equipped with a force transducer in order to measure both external forces acting on the body, i.e. ground reaction force and poling reaction force.

Procedures

Submaximal trials were individually matched at the same subjective intensity using the Borg's Scale (6-20) Rate of Perceived Exertion directed at 10, 13, and 16 for the respective trials, corresponding to the Norwegian Olympic Committee intensity system 1-3 (Seiler & Tønnessen, 2009). Thus, each subject performed independently of each other but in accordance to their own internal effort and performance level. All athletes had been performing extensive endurance training for at least six years and were considered experienced in subjective control of intensity. MAX was performed with maximum effort, although participants used the initial ~20 s to reach a power production that seemed sustainable for 3 min. Respiratory variables and heart rate were measured continuously and blood lactate values were collected immediately after all trials in order to objectively control for intensity. The participants performed all trials at their own freely chosen cycle rate. The integrated SkiErg performance monitor (PM4) displayed the instantaneous net DP power, allowing each subject to monitor and maintain the power production as stable as possible throughout the submaximal trials. One researcher also guided the participants to keep a stable power production and standardized encouragement was given during MAX.

Double Poling Ergometer

Double poling was performed on a modified Concept2 SkiErg (Concept2 Inc., Morrisville, VT, USA). The damper setting was set at level 1 (the lowest drag resistance) since the ergometer flywheel operates such that increasing poling force increases air resistance. Thus, increasing poling force (ergometer power) does not lead to the same decrease in poling time (and thus, time of force generation) as when increasing poling force while DP on a treadmill or on-snow skiing (Linnamo et al., 2013). Therefore, the lowest damper level was chosen since this is most similar to treadmill or skiing DP with respect to poling times.

Physiological measurements

Respiratory variables and oxygen consumption (VO_2) was continuously measured by open-circuit indirect calorimetry using an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). At the beginning of each test day, the O_2 and CO_2 gas analyzers were calibrated against a known mixture of gases (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany), and the expiratory flow meter was calibrated with a 3 L volume syringe (Hans Rudolph Inc., Kansas City, MO). Blood lactate values was obtained from a 20 µl blood sample collected from the fingertip and analyzed using a Biosen C_line Sport lactate analyzer (EKF-diagnostic GmbH, Barleben, Germany). Heart rate was continuously recorded using a Suunto t6c heart rate monitor (Suunto Oy, Vantaa, Finland) and synchronized with the VO_2 measurement system.

Kinetic measurements

To measure poling forces, the DP ergometer was instrumented with a Futek Miniature Tension and Compression Load Cell (Futek LCM200, capacity 250 Ib, non-linearity ± 0.5%, hysteresis ± 0.5%, weight 17 g, Futek Inc., Irvine, CA, USA) mounted in series by Rod End Bearing (Futek, GOD00730, capacity 5100 Ib) to the drive cord inside the casing. The force cell was calibrated against a range of forces of known magnitude. All trials were performed with the participants standing on a Kistler force plate (Kistler 9286BA, Kistler Instrumente AG, Winterthur, Switzerland). The force plate was placed in front of the ergometer at a distance where the athletes were able to create similar movement characteristics as on-snow

DP. All force measurements were zeroed before and offsets were removed at the start of each measurement. Force data was sampled at 500 Hz, low-pass filtered (8th order, zero lag Butterworth) and synchronized with kinematic data using the Oqus system (Qualisys AB, Gothenburg, Sweden).

Kinematic measurements

The Oqus 3D motion analysis system consisting of seven infrared cameras were placed around the subjects in order to capture three-dimensional position characteristics of passive reflective markers at a sampling frequency of 100 Hz. Four markers were fixed on the ergometer in order to measure poling distance; two on the right and left handles and two on the right and left top of the ergometer body at the point where the ropes enters the ergometer.

After shaving the skin, the same researcher placed seven spherical reflective markers on the left side of the body at anatomical landmarks using double sided tape (3M, USA). These landmarks were on the shoe at the distal end of the fifth metacarpal of the foot, the lateral malleolus (ankle), the lateral epicondyle (knee), the greater trochanter (hip), the lateral end of the acromion process (shoulder), the lateral epicondyle of humerus (elbow), and the styloid process of ulna (wrist). Joint angles were defined as the angle between the two segments on either side of the respective joint. For example, the knee joint angle was defined as the angle between hip, knee and ankle axes. In this study, the DP movement was assumed to be symmetrical in the sagittal plane, and any medio-lateral movements were neglected.

For example, although the shoulder joint shows substantial abduction and may thus generate a small rotational moment (Holmberg et al., 2005), only flexion-extension was taken into consideration. Left side data was multiplied by two so that all joint-specific powers represent both left and right side joints. Additionally, two reflective markers were placed on the force plate in order to adjust the force plate center to a 3D coordinate center. The coordinate system was calibrated by wand between each second participant in order to maintain high-quality data.

Kinematic data was low-pass filtered (8th order, zero lag Butterworth). Kinematics and kinetics were recorded from the start of the trials and 20 DP cycles with steady state power production were used for further analyses. All data was recorded and synchronized simultaneously using the Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). Data was stored offline for further processing in MATLAB 8.1.0. (R2013a, Mathworks Inc., Natick, MA, USA).

Data analysis

The body was approximated as a system of linked rigid segments connected by frictionless revolute joints. The sagittal plane limb segments were defined as foot, leg, thigh, trunk (including head), upper arm, and forearm. Segmental masses, moments of inertia and center of masses were calculated as a percentage of total body mass by use of regression equations and the parameters reported by de Leva (1996). Joint center positions of the elbow, shoulder, hip, knee, and ankle were taken from the position data. Linear and angular velocities and accelerations of limb segments, and velocity of the poling handles relative to the ergometer, were calculated by finite differentiation of position data with respect to time, using a 5-point differentiation filter. By the use of inverse dynamics techniques (Elftman, 1939), Newtonian equations of motion were applied to calculate net muscle moments at the joints. The dot product of joint net muscle moments and joint angular velocity yields joint power. When net joint moment and angular velocity are in opposite direction, power is negative. This means that energy is absorbed at the respective joint.

The sum of ankle, knee, and hip joint power was defined as lower extremities (LowExt) power. These joints' moments of force were calculated on the basis of the ground reaction force (GRF). Upper extremities (UppExt) power was defined as the sum of elbow and shoulder power. Here, the moments of force was calculated from the poling reaction force. The division between UppExt and LowExt in the calculations was done to avoid the accumulating errors in the calculations of the joint moment of force in the more proximally located joints.

E_{body} was calculated as the sum of kinetic (E_{kin}), potential (E_{pot}) and rotational (E_{rot}) energy of all segments *i* (I).

$$E_{body} = E_{kin} + E_{pot} + E_{rot} = \sum ½\cdot m_i\cdot v^2 + m_i \cdot g\cdot h + ½\cdot I_i\cdot \omega^2 \qquad \text{(I)}$$

m_i is the mass of the segments *i*, v the horizontal and vertical velocity of m_i, I_i the moment of inertia of m, ω the angular velocity of m_i, g the gravitational constant ($9.81 m\cdot s^{-2}$) and h the height of m_i. E_{body} was then differentiated with respect to time to yield P_{body}, which is the rate of change in E_{body}. P_{body} is zero whenever there is no change in E_{body}. When net E_{body} decreases (e.g. $CoM_{(t)}$ lowering), P_{body} becomes negative and E_{body} is transferred to either the external environment (P_{poling}), and/or is absorbed by the joints (negative joint power). When net E_{body} increases (e.g. $CoM_{(t)}$ heightening), P_{body} becomes positive as more E_{body} is produced by the muscles (positive joint power) than absorbed.

Moreover, movements in the pelvis/trunk were not accounted for, although substantial flexion-extension occurs in the numerous joints that the pelvis/trunk consists of. Therefore, the sum of Ppoling, Pbody and the individually calculated joint powers did not equal zero, and this difference was thus defined as trunk power.

For all variables, average values were obtained from ~20 cycles with steady state power production (data checked visually), which were interpolated. The effect of intensity was tested both for the whole DP cycle, the PPh and the RPh. One cycle was defined from the start of the displacement (maximum negative value) of the handles relative to the ergometer to the subsequent maximum negative value. The division into a PPh and a RPh was defined by the handle displacement reaching its maximum positive value relative to the ergometer. Poling time (PT) was defined as the PPh time, cycle rate (CR) as the number of poling cycles per second (Hz), cycle time (CT) as time spent over the complete cycle, and relative PT as the percentage of PT to CT.

Statistical Analysis

All data were checked for normality and are presented as means ± standard deviation (SD) in the table and as means ± standard error of the mean (SEM) in the figures. A two-way repeated measures ANOVA was performed on the absolute power of upper and lower extremities, the trunk and P_{body} to test for possible interactions as intensity increased. A one-way repeated measures ANOVA was performed to test if there were any significant changes on either of the relative variables as intensity increased. A Bonferroni post-hoc test was applied to identify at which trials any possible significant changes were located between LOW, MOD, HIGH and MAX. Statistical significance was set at $P < 0.05$. All statistical tests were performed using SPSS version 21.0 (SPSS, Inc., Chicago, IL, USA).

Results

Cycle characteristics and physiological responses

Cycle characteristics and physiological variables are displayed in **Table 1**. As intensity increased from LOW to MAX, CT decreased and CR increased ($P < 0.001$). While the absolute PT decreased, the relative PT was stable from LOW to HIGH and then increased from HIGH to MAX ($P < 0.001$). Peak poling force and P_{poling} increased significantly across all trials ($P < 0.01$). Measured RPE did not differ from requested RPE in any case. Blood lactate increased significantly across all trials ($P < 0.01$). VO_2 significantly increased from LOW to MAX ($P < 0.01$), and DP specific VO_{2peak} was 66.7 ± 5.1 ml/kg^{-1}/min^{-1}. Relative VO_2 and relative HR increased from LOW to HIGH ($P < 0.001$).

Table 1. Cycle characteristics while ergometer double poling at increasing intensities (mean ± SD).

	LOW	MOD	HIGH	MAX
CT (s)	1.36 ± 0.15^{c,d}	1.29 ± 0.15^{c,d}	1.21 ± 0.16^{a,b,d}	1.04 ± 0.11^{a,b,c}
CR (Hz)	0.74 ± 0.08^{c,d}	0.78 ± 0.09^{c,d}	0.84 ± 0.11^{a,b,d}	0.97 ± 0.11^{a,b,c}
PT (s)	0.62 ± 0.06^{c,d}	0.58 ± 0.05^{c,d}	0.54 ± 0.04^{a,b,d}	0.49 ± 0.04^{a,b,c}
PT_rel (%)	45.4 ± 2.1	44.9 ± 2.2^{d}	44.9 ± 2.3^{d}	47.3 ± 1.8^{b,c}
Fpp (N)	273.5 ± 61.2^{b,c,d}	363.6 ± 81.3^{a,c,d}	433.4 ± 86.2^{a,b,d}	517.4 ± 95.1^{3a,b,c}
Ppoling_peak (W)	655.8 ± 188.9^{b,c,d}	941.4 ± 302.0^{a,d}	1163.4 ± 500.6^{a,d}	1730.1 ± 378.3^{a,b,c}
Ppoling_mean (W)	115.8 15.5^{b,c,d}	165.8 33.6^{a,c,d}	214.1 38.1^{a,b,d}	306.2 38.0^{a,b,c}
Requested RPE	10	13	16	20
Actual RPE	9.0 ± 1.7^{b,c,d}	12.0 ± 1.5^{a,c,d}	15.0 ± 1.3^{a,b,d}	19.0 ± 0.3^{a,b,c}
BLa (mmol/L^{-1})	1.87 ± 0.55^{b,c,d}	3.24 ± 0.77^{a,c,d}	5.67 ± 0.82^{a,b,d}	12.21 ± 1.75^{a,b,c}
VO_2 (ml/kg^{-1}/min^{-1})	31.7 ± 3.9^{b,c,d}	41.2 ± 6.0^{a,c,d}	51.3 ± 7.2^{a,b,d}	66.7 ± 5.1^{a,b,c}
VO_2_rel (%)	47.5 ± 4.0^{b,c}	61.7 ± 7.0^{a,c}	76.8 ± 8.0^{a,b}	100.0 ± 0.0
HR_rel (%)	67.7 ± 4.0^{b,c}	79.5 ± 3.8^{a,c}	89.9 ± 3.5^{a,b}	100.0 ± 0.0

CT, cycle time; CR, cycle rate; PT, poling time; PT_rel, relative PT; Fpp, peak poling force; Ppoling_peak, peak poling power; Ppoling_mean, net cycle poling power; RPE, rate of perceived exertion (Borg Scale); BLa, blood lactate; VO_2, oxygen consumption; VO_2_rel, relative oxygen consumption; HR_rel, relative heart rate.
Values are mean ± SD, N=9, all P values <0.05.
^{a} different from LOW, ^{b} different from MOD, ^{c} different from HIGH, ^{d} different from MAX.

Basic description of the power changes during the DP cycle

A stick diagram of a typical example of a skier performing DP at maximal intensity is shown in **Fig. 1**. Within the PPh (~15 to ~35% CT), the GRF as well as the poling force increases; the two forces being in opposite direction. During the RPh, the GRF is stable at first (~50 to ~75% CT) before it rapidly decreases (~75 to 100% CT). **Fig. 2A** and **3A** shows the relationship between P_{poling}, P_{body} and the total sum of the joint powers over the cycle at LOW and MAX, respectively. **Fig. 2B** and **3B** show the total sum of the joint powers from **A** divided into LowExt, UppExt and trunk power.

Whenever there is no P_{poling}, the total sum of joint powers equals P_{body}. That is, all muscle work is used to increase or maintain E_{body}. **Fig. 4** shows the effect of intensity on the joint-specific powers of the same skier, together with P_{poling}, GRF, P_{body}, vertical $CoM_{(t)}$ movement, and joint angle changes.

Poling phase. Due to the simultaneous ankle, knee, and hip joint flexion starting at the end of RPh and lasting approximately 50% of PPh (**Fig. 4E**), the $CoM_{(t)}$ moves downward and forward (**Fig. 1; Fig. 4D**) as the skier leans forward against the poling handles. P_{poling} starts to rapidly increase 10% into the cycle, with peak P_{poling} occurring ~22% into the cycle, before rapidly decreasing towards zero. P_{body} is also around zero during the first ~10% of the cycle (**Fig. 4C**), which means that there is no change in E_{body}. A rapid negative increase in P_{body} then takes place with its negative peak occurring simultaneously as peak P_{poling} (**Fig. 2A; 3A**). At the same point in time as peak P_{body}, the total sum of joint powers also has its negative peak, meaning that in total the muscles absorb energy.

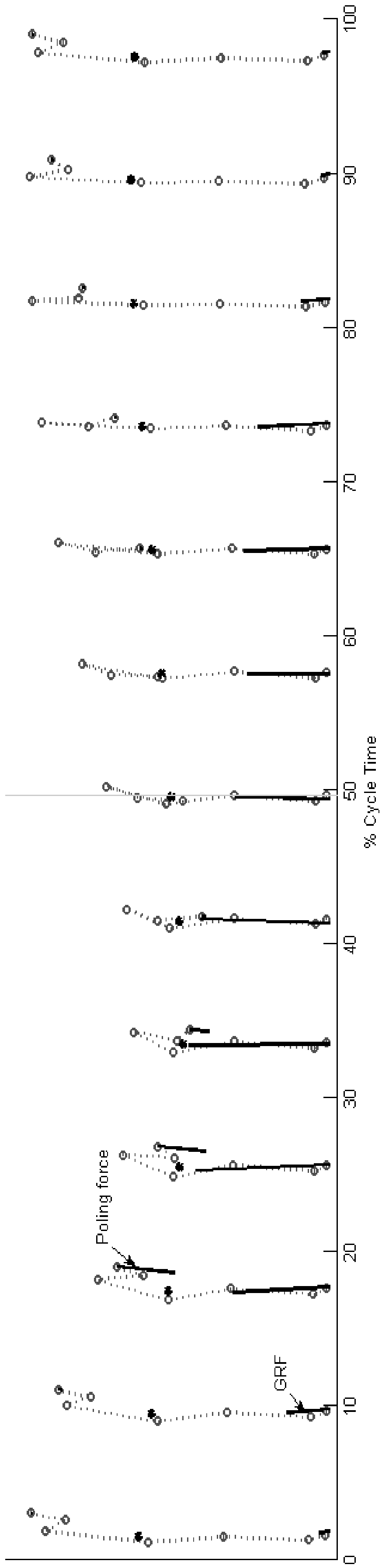


Fig. 1. Stick diagram of one skier preforming ergometer double poling at maximal intensity. The greyed vertical line at ~50% CT represents the end of the poling phase. The black line at the foot represents the ground reaction force (GRF). The black line at the hands represents the poling force. The black dot at the height of the pelvis is the position center of mass.

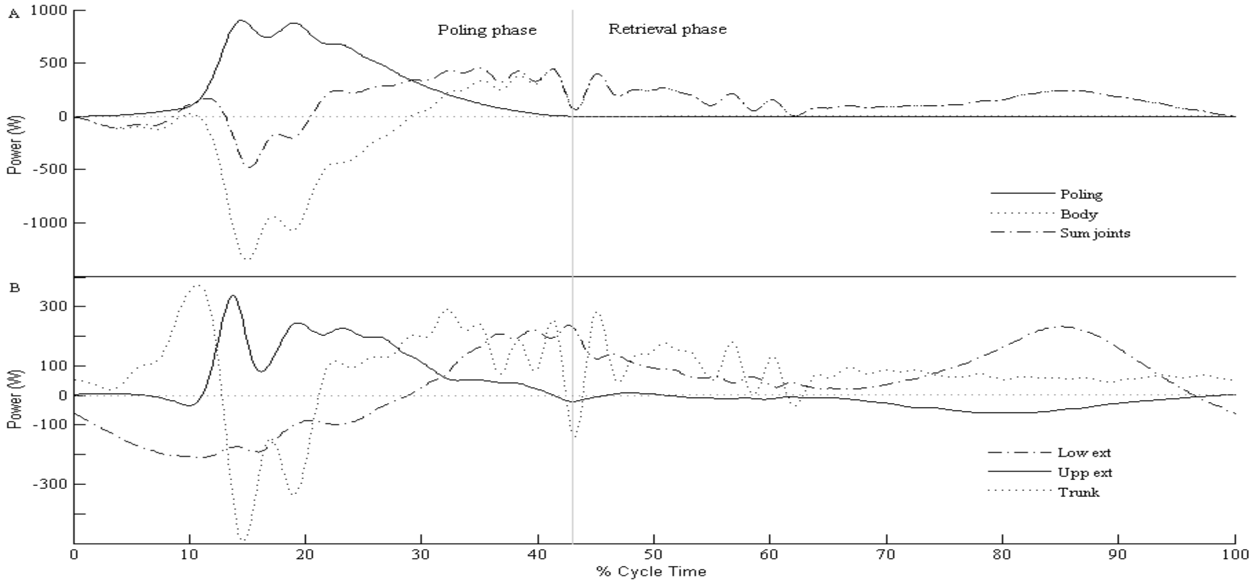


Fig. 2. Power normalized to 100% cycle time for one subject performing ergometer double poling at intensity LOW. Vertical line represent end of poling phase. Poling, poling power; Body, total body power; Sum joints, sum of all joints including trunk (A); Low ext, ankle, knee, and hip joint power; Upp ext, elbow and shoulder joint power; Trunk, trunk power (B).

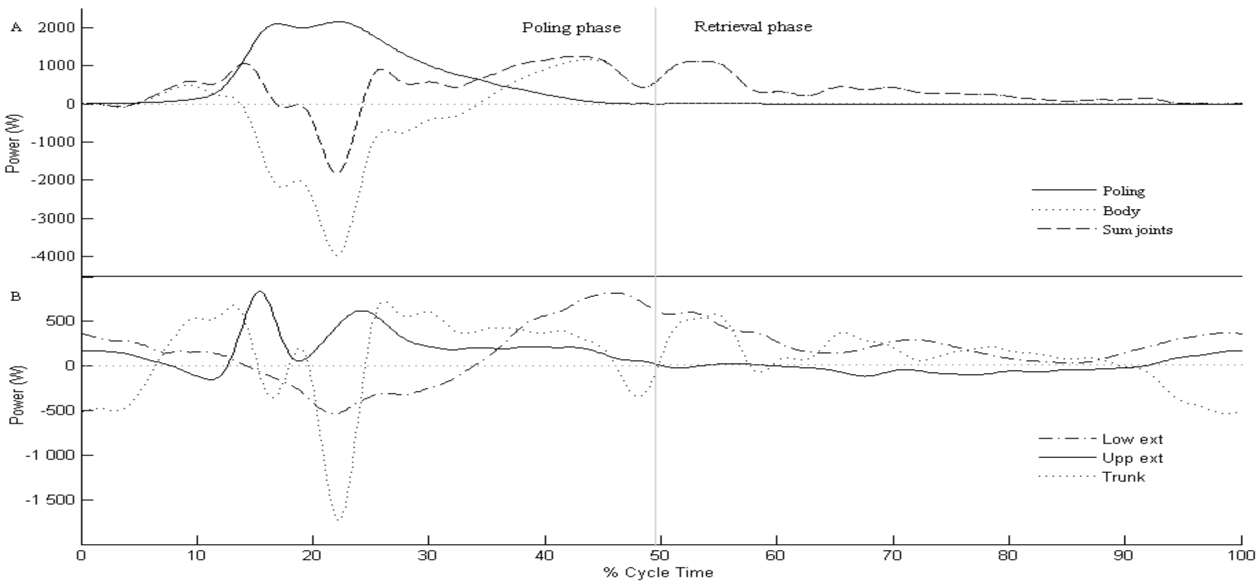


Fig. 3. Power normalized to 100% cycle time for one subject performing ergometer double poling at intensity MAX. See Fig. 3 for abbreviations.

Since negative P_{body} means that E_{body} decreases, some of E_{body} is transferred to external work (i.e. P_{poling}). Therefore, whenever the total sum of joint powers is negative, P_{body} amounts to 100% of P_{poling}. After its negative peak, P_{body} then increases and becomes positive towards the end of PPh. Simultaneously, the LowExt joints start extending and the $CoM_{(t)}$ is moved upwards. As E_{body} first decreases (i.e. negative P_{body}) and then increases (i.e. positive P_{body}) until its original value is reached at the end of RPh, the net P_{body} equals zero.

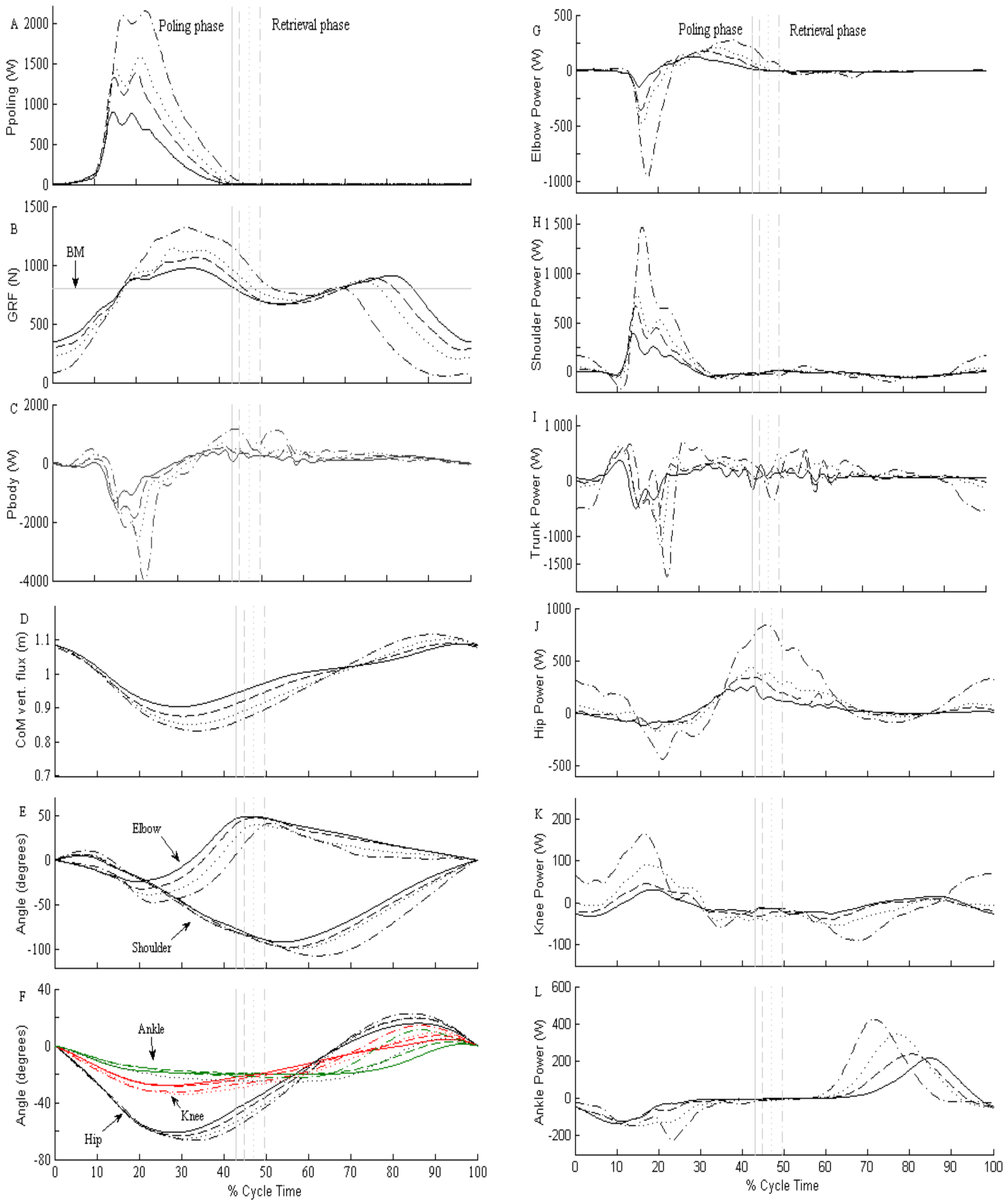


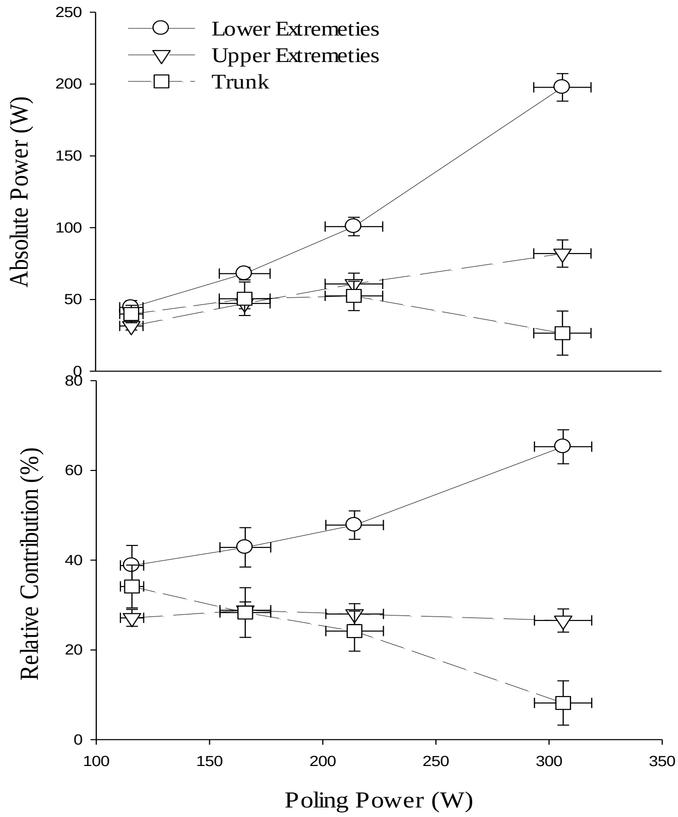
Fig. 4. Behavior of: Ppoling, poling power (A); GRF, ground reaction force (B); Pbody, total body power (C); CoM vert. flux, vertical movement of $CoM_{(t)}$ (D); joint angle changes (E; F); and joint-specific powers (G to L) normalized to 100% cycle time for one subject performing ergometer double poling at LOW (*solid line*), MOD (*dashed line*), HIGH (*dotted line*), and MAX (*dash-dotted line*) intensity. Vertical greyed lines represent end of poling phase at the same respective intensities. Worth a note is the increase in relative poling time (indicated by vertical greyed lines) as intensity increased, while the time period of P_{poling} generation was less affected.

The negative peak in the total sum of joint powers, both at LOW and MAX, occurs simultaneously as peak P_{poling} (**Fig. 2A; Fig. 3A**). This is explained by the negative LowExt and trunk power at the same point in time (**Fig. 2B; Fig 3B**). The UppExt only produces positive power across all intensities (**Fig. 3B**), with two peaks, both at LOW and MAX. The drop in between can be explained by the rapid decrease in shoulder power from a very high peak (first UppExt peak) down to a more stable level, simultaneously as elbow power changes from negative to positive power (second UppExt peak) (**Fig. 4G;H**). For most skiers the elbow joint operates with a clear flexion-extension movement (**Fig. 4E**). Individual differences must be mentioned, however. Some skiers (n=4) only performed elbow extension (no flexion) during the PPh and thus yielded positive elbow power. The shoulder joint shows a small flexion period at the start of PPh, but changes to extension during P_{poling} generation for all skiers (**Fig. 4E**).

Retrieval phase. The change from negative to positive P_{body} occurs as $CoM_{(t)}$ starts heightening, due to the hip and knee joints changing from flexion to extension. At the about time point in time, P_{poling} decreases to zero. LowExt power also becomes positive (**Fig. 2B; 3B**) due to the rapid change from negative to positive hip joint power (**Fig. 4J**). Thus, the heightening of $CoM_{(t)}$ and the body repositioning starts before actual end of PPh, as can be seen in **Fig. 1**. P_{body} reaches a positive peak in the transition from PPh to RPh, meaning that E_{body} here is rapidly increasing. All the positive LowExt and trunk power is now used to increase E_{body} and to reposition the body for the subsequent cycle. At submaximal intensities, P_{body} and the total sum of joint powers rather quickly levels off during the first part of the RPh. This demonstrates that the skier rather quickly resumes an upright position (**Fig. 1; 4I**). At MAX, however, both P_{body}, LowExt and trunk power are much higher during the RPh and at the start of the PPh. This demonstrates that more positive muscle work is done in preparation for the subsequent cycle (**Fig. 2B; 3B**).

Effects of intensity on power over the cycle - statistics

Net cycle. **Fig. 5** shows the group means of the absolute power and the relative contributions of the UppExt, LowExt and trunk to net cycle P_{poling}. An interaction was revealed between absolute UppExt, LowExt and trunk power, as intensity increased ($P < 0.001$). The interaction was explained by an increase in the relative contribution of the LowExt, from 39 ± 14 % at LOW to 48 ± 9 % at HIGH, further increasing to 65 ± 11% at MAX ($P < 0.001$). The relative



.Fig. 5. Absolute power and relative contribution to net cycle poling power for nine subjects performing ergometer double poling at increasing intensities (Mean ± SEM).

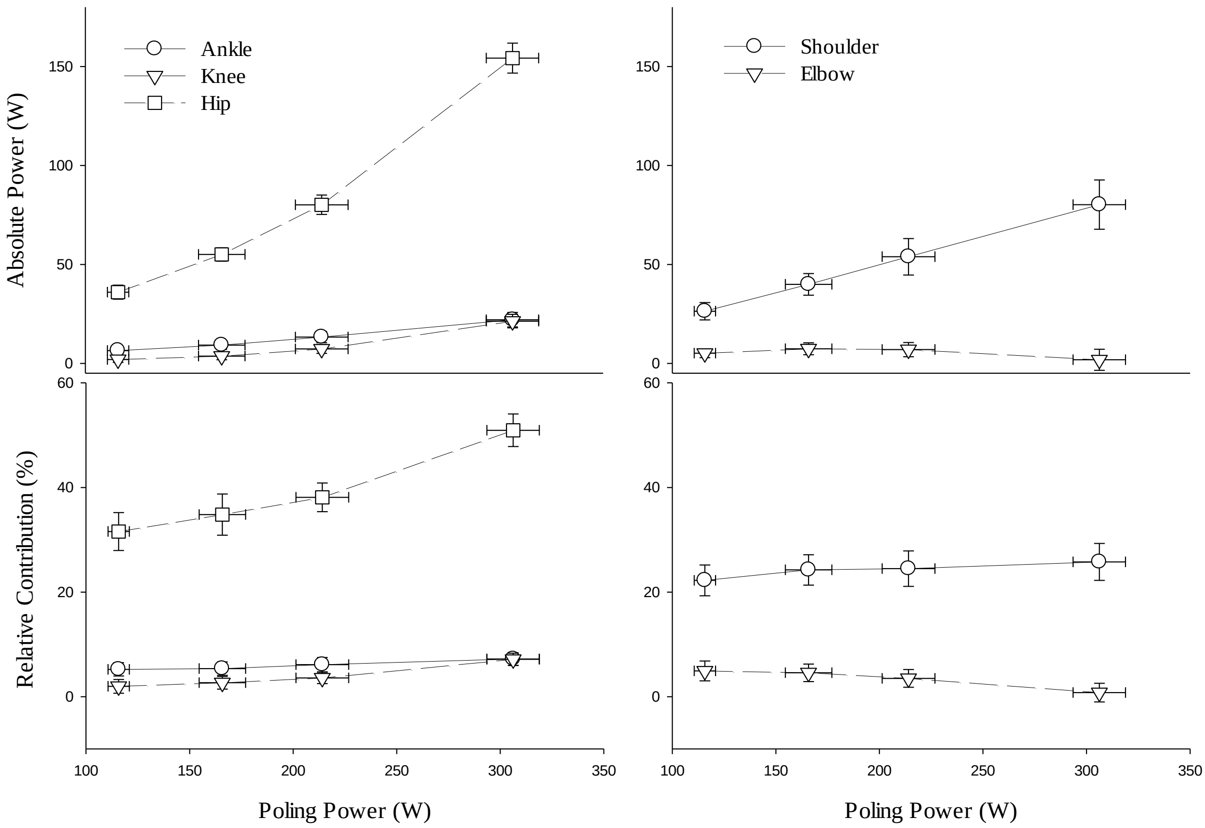


Fig. 6. Joint-specific absolute power and relative contribution to net cycle poling power for nine subjects performing ergometer double poling at increasing intensities (Mean ± SEM).

contribution of the trunk inversely decreased from 34 ± 14% at LOW to 24 ± 13 % at HIGH ($P < 0.05$), and to 8 ± 15 % at MAX ($P < 0.01$). No significant effect of intensity was found between LOW and MOD and between MOD and HIGH for the LowExt and trunk, respectively. The relative contribution of the UppExt was stable at 28 ± 6% across all trials, with no significant changes.

Fig. 6 shows the absolute powers and relative contributions of the specific joints to net cycle P_{poling}. No significant effects of intensity were found for the elbow, shoulder, and ankle joints' relative contributions. The knee joints' relative contribution increased from 2 ± 4 % at LOW to 7 ± 3 % at MAX ($P < 0.001$). The hip joints' relative contribution increased, from 38 ± 8 % at HIGH to 51 ± 9 % at MAX ($P < 0.01$).

Poling phase. **Fig. 7** shows the absolute powers and the relative contributions of the UppExt, LowExt, trunk and P_{body} as a function of P_{poling} within the PPh. Mean P_{poling} significantly increased from 254 ± 36 W at LOW to 369 ± 79 W, 476 ± 77 W, and 646 ± 74 W at MOD, HIGH, and MAX, respectively (all trials, $P < 0.001$).

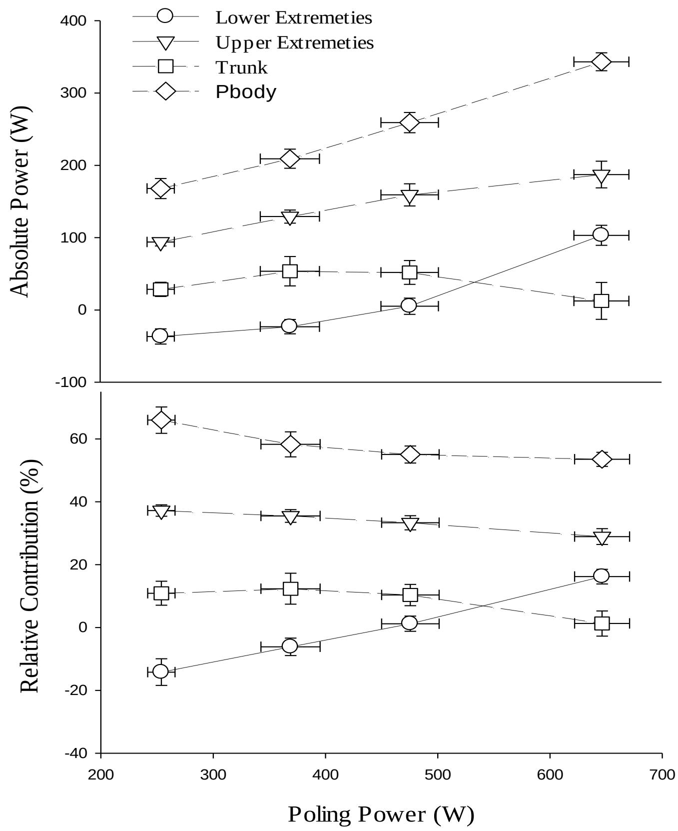


Fig. 7. Absolute power and relative contribution to poling power within poling phase for nine subjects performing ergometer double poling at increasing intensities (Mean ± SEM).

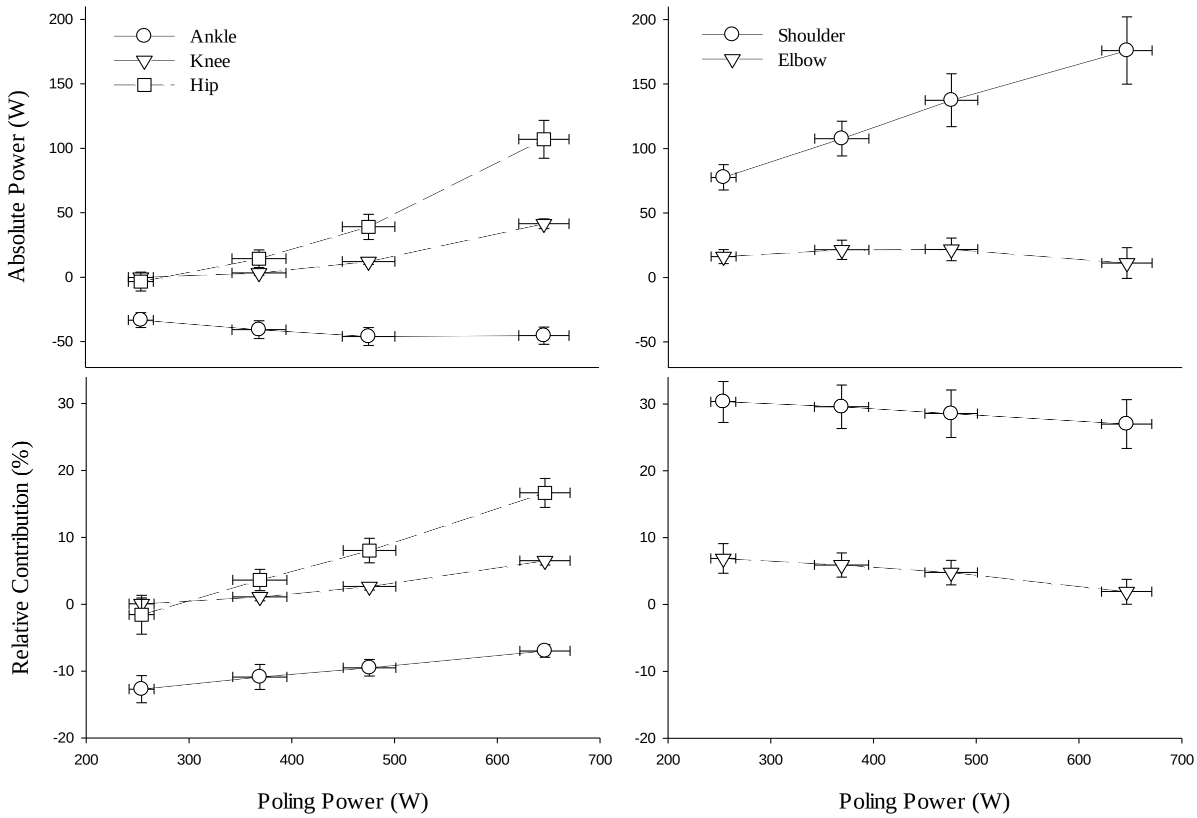


Fig. 8. Joint-specific absolute power and relative contribution to poling power within poling phase for nine subjects performing ergometer double poling at increasing intensities (Mean ± SEM).

An interaction in absolute powers between the UppExt, LowExt, trunk and P_{body} was found ($P<0.001$); the LowExt even changed from absorbing to producing power, while the UppExt, trunk and P_{body} showed a slight non-significant decrease in their relative contributions. More specifically, P_{body} decreased from 66 ± 13 % at LOW to 54 ± 7 % at MAX ($P = 0.060$), while the relative contribution of the LowExt changed from -14 ± 13 % at LOW to 1 ± 7 % at HIGH ($P < 0.05$) and to 16 ± 7 % at MAX ($P < 0.001$). The relative contribution of the UppExt decreased just non-significantly from 37 ± 6 % at LOW to 29 ± 8 % at MAX ($P = 0.051$).
The relative contribution of the trunk was stable at 11 ± 12 % from LOW to HIGH and decreased significantly to 1 ± 12 % at MAX ($P < 0.01$).

Fig. 8 shows the absolute powers and relative contributions of the specific joints to P_{poling} within the PPh. The relative contribution of the ankle joints changed significantly from -13 ± 6 % to -7 ± 3 % from LOW to MAX ($P < 0.05$). The relative contribution of the knee joint was 0 ± 3 % at LOW and increased significantly to 7 ± 2 % at MAX ($P < 0.01$). The relative contribution of the hip joint changed significantly from -2 ± 9% at LOW to 8 ± 6% at HIGH, and further increased significantly to 17 ± 6 % at MAX ($P < 0.001$). No significant change was found for the shoulders joints' relative contribution, which was stable at ~28 ± 11 %. The elbow joints' relative contribution was stable from LOW to HIGH at ~6 ± 6 % before decreasing significantly to 2 ± 6 % from HIGH to MAX ($P < 0.01$).

Retrieval phase. **Fig. 9** shows the absolute powers and the relative contributions of the trunk, hip, knee, and ankle joints to P_{body}. P_{body} increased significantly across all trials, from 141 ± 38 W at LOW to 171 ± 38 W, 213 ± 44 W, and 309 ± 41 W at MOD, HIGH and MAX, respectively ($P < 0.001$). A significant interaction was found between trunk, hip, knee and ankle absolute powers as intensity increased ($P < 0.001$). The trunk's relative contribution decreased significantly from 37 ± 12 % at LOW to 29 ± 12 %, 26 ± 12 % and 14 ± 11 % at MOD, HIGH, and MAX, respectively ($P < 0.05$). The hip joints' relative contribution was stable from LOW to HIGH at ~52 ± 14 % before increasing significantly to 63 ± 12 % at MAX ($P < 0.05$). No significant effects of intensity were found for the ankle and knee joints relative contribution.

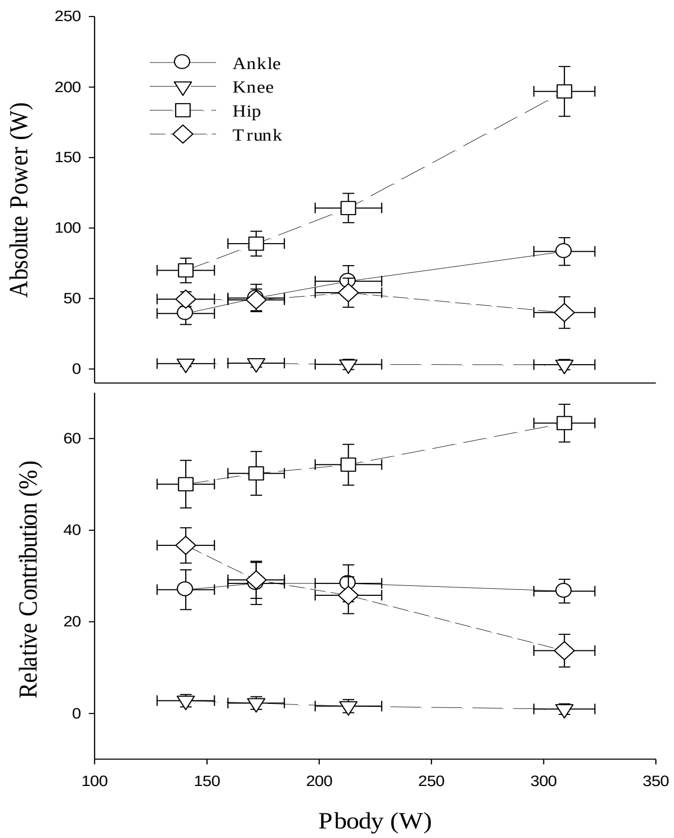


Fig. 9. Absolute power and relative contribution to total body power (P_{body}) within the retrieval phase for nine subjects performing ergometer double poling at increasing intensities (Mean ± SEM).

Discussion

The present study investigated the effect of increasing intensity on the absolute and relative contributions of joint-specific powers and E_{body} to P_{poling} within the different phases of the DP cycle in elite cross-country skiers. One main finding was that during propulsion, the utilization of total body mechanical energy, P_{body}, is the main contributor to poling power both at low and maximal intensity. Furthermore, over the cycle most power is produced by the body's core, i.e. the hip, trunk and shoulder joints. The lower extremities show substantial increase in relative contribution as intensity increases. Mostly, this was due to an increase in the P_{body} during retrieval phase, in which the LowExt fully accounted for. Additionally, the lower extremities drastically changed their role during poling phase as intensity increased, i.e. changed from absorbing to generating energy from LOW to MAX. Furthermore, elite skiers both generate and absorb substantial amounts of energy over the cycle, mostly due to the vertical flux in $CoM_{(t)}$ as a way of transferring P_{body} to P_{poling}.

The finding that P_{body} was the main contributor to P_{poling} can be explained by the fluctuation of energy from the muscles (joint-specific) to the body (P_{body}) and further to external work (P_{poling}) during the cycle. Across all intensities, the total sum of joint powers amounted to 100 % of P_{body} during the RPh, i.e. all muscle work was done to increase E_{body}. At the start of the PPh, E_{body} had reached its maximal and stable value as P_{body} was zero, i.e. there was no change in E_{body}. By LowExt joint flexion and eccentric muscle work (negative power), $CoM_{(t)}$ was lowered in a forward direction while the shoulder and elbow joints produced and absorbed power, respectively. Thus, P_{poling} reached its peak with the total sum of joint powers being negative. Therefore, 100 % of P_{poling} originated from P_{body}. Even if the shoulder and the elbow joints had worked isometrically with no flexion or extension, P_{body} would still have accounted for 100% of P_{poling} through the forward lowering and leaning of $CoM_{(t)}$ and the upper body against the poling handles. This is logical considering that the upper body mass accounts for ~68% of total body mass (Winter, 1990). Obviously, energy fluctuated in a chain during the DP cycle, and the net energy equalled zero. That is, the decrease in E_{body} during PPh is transferred to P_{poling} and partly absorbed by the LowExt joints. Thereafter, E_{body} increases back up to its original value, starting at the end of PPh and continuing throughout RPh. This is demonstrated by the high absolute hip, trunk and ankle powers.

Although this is the first study to investigate these energy fluctuations in more detail, previous studies have emphasised that such energy fluctuations likely occurs due to the lower extremities becoming increasingly important as DP intensity increases. This in turn is accompanied with an enhanced flux in the vertical $CoM_{(t)}$ movement, all in order to generate higher poling forces over an often much shorter poling time (Holmberg et al., 2006; Lindinger et al., 2009b; Rud et al., 2013). Therefore, the finding that the relative contribution of the LowExt drastically increased from 39% at LOW to 65% at MAX is in line with our hypothesis.

An important reason for the increase in the relative contribution of the LowExt over the cycle was that the behaviour of LowExt power changed during the PPh (Fig. 2B; 3B). At LOW, the LowExt continuously absorbed energy from the beginning of PPh, while at MAX the LowExt absolute power did not become negative until ~13% of the cycle. This observation has to be explained together with the finding that the relative contribution of P_{body} in fact tended to decrease, from 66% at LOW to 54% at MAX. This is opposite to what was expected. One possible explanation for these two alterations is that during LOW, the available amount of E_{body} to be transferred to P_{poling} is more than required. Thus, the LowExt has to absorb more of the E_{body}, as it is lowered through eccentric muscle contractions (negative trunk, hip and ankle power). If this absorption did not take place, there might have been too much E_{body} transferred to P_{poling}. One might thus have generated more P_{poling} than required. The DP movement might also have become uncontrolled and less smooth, requiring other joints to produce more work to maintain balance and/or to maintain a stable P_{poling}; as if e.g., one did not rely on P_{body} at all, but fully on positive UppExt power to generate P_{poling}. During MAX, however, cycle rate increased to 58 cycles/min compared to 45 cycles/min at LOW, which requires more positive muscle work just to accelerate the various segments relative to each other and to $CoM_{(t)}$. Furthermore, the much higher poling forces at MAX increased the air resistance of the ergometer flywheel. This might have required that the LowExt, instead of absorbing and controlling the lowering of $CoM_{(t)}$, now must have actively pulled the $CoM_{(t)}$ and the upper body downwards. Still, at MAX, the LowExt changed from producing to absorbing energy, approximately at peak P_{poling}, where the hip joint power (Fig. 4J) and the ankle joint (Fig. 4L) show high negative peaks. These negative peaks can be explained by the high GRF (Fig. 4B) occurring simultaneously and in the opposite direction of the poling reaction force (Fig. 1). The forces acting in opposite directions are necessary to counteract the poling action force, to maintain forward-backward balance as well as position on the force plate. These latter mechanisms are similar to the ones observed for the LowExt while treadmill DP at high speeds (Holmberg et al., 2005; Lindinger et al., 2009b). Taken together, at MAX, more positive joint power (hip especially) is required in order to generate the higher amount of P_{body} and to generate enough poling force by actively lowering $CoM_{(t)}$. The latter is especially important considering that the relative poling times increased from MOD and HIGH to MAX (Table 1).

An interesting consideration is the possible reutilisation of elastic energy in a stretch-shortening cycle (SSC), that might appear because of the changes from flexion to extension of the LowExt; this combined with negative followed by positive power, both in the hip joint and in P_{body} (van Ingen Schenau, G. J. et al., 1997a; G. J. van Ingen Schenau, Bobbert & de Haan, 1997b). For a SSC to be evident in whole-body movements such as DP, P_{body} should negatively increase as E_{body} decreases below its original value at the initiation of PPh. Some E_{body} might then be stored as elastic energy in series-elastic elements of the muscle-tendon complex during joint flexion phase (eccentric/concentric muscle contraction) which later is reutilised in the immediately following joint extension phase (concentric muscle contraction). In typical SSC activities such as fast level running, E_{body} rapidly decreases during ground contact with $CoM_{(t)}$ lowering (energy absorbed) and then rapidly increases up to its original value during ground push-off with $CoM_{(t)}$ heightening (energy generated). Thus, P_{body} rapidly changes sign from negative to positive at the same point in time. Simultaneously, E_{body} starts increasing from its lowest value up to its original value, if enough energy has been stored and released to affect P_{body} (Cavagna, Saibene & Margaria, 1964; Cavagna et al., 1976). Furthermore, the total sum of joint powers over the running cycle usually equals zero, i.e. the amount of negative and positive joint power is often the same in SSC activities. Only partly does the behaviour of P_{body} and hip power agree with the abovementioned. P_{body} does show a rapid negative increase and becomes positive the same point in time as the hip joint changes from flexion to extension with hip joint power also changing from negative to positive. However, the increase from negative peak P_{body} does not occur as rapidly as in e.g. running, and P_{body} does not level off at around zero (E_{body} is restored to its original value) until late into RPh. Finally, the total sum of joint powers in the present study yielded more positive power, instead of being zero as in typical SSC activities (van Ingen Schenau, G. J. et al., 1997a).

Following the same logic, it is also interesting to investigate if the similar patterns regarding joint kinematics and power behaviour occur at the elbow and shoulder joints. Both Lindinger, Holmberg, Müller and Rapp (2009a) and Zoppirolli et al. (2013) have discussed the possibility for a SSC in these joints as a way of optimizing DP performance and efficiency. In the present study, the elbow joint showed typical stretch-shortening kinematics with a flexion phase followed by an extension phase. Thus, the elbow joint power showed a very high negative peak as intensity increased, which was immediately followed by an extension and positive joint power. This is the same pattern as found while treadmill DP (Lindinger et al., 2009a). However, at the point in time where the elbow joint changes from flexion to extension, P_{body} is actually at its negative peak, i.e. E_{body} is at its lowest value, and P_{body} does not become positive as would be typical for a SSC. For the shoulder joint there is basically no flexion occurring, except for a very short flexion period at MAX. Thus, while the elbow joint is flexing the shoulder joint is simultaneously extending (Fig. 4G,H). Interestingly, for the skiers, who only extended the elbow during PPh (n = 4), the shoulder peak power was much lower than for those, who first flexed the elbow. The skiers, who only extended the elbow, also generated lower poling forces but over a longer period of time. Additionally, they had a lower flux in the $CoM_{(t)}$ as they,at all intensities, produced less net P_{poling}. The negative peak elbow power for the better skiers also occurred almost at the exact same time as the positive peak shoulder power (as demonstrated by the skier in Fig. 4). This finding might imply that negative elbow power is transported and reappears as positive shoulder power. Such power transportations between joints are made possible through bi-articular muscles (van Ingen Schenau, G. J., 1990; van Ingen Schenau, G. J., Bobbert & Rozendal, 1987; van Ingen Schenau, G. J., Boots, de Groot, Snackers & van Woensel, 1992), which is the case for long head of the m. triceps brachii, which serves as an elbow extensor as well as a shoulder extensor muscle.

Because of the causal relationship between the direction and magnitude of an external force and the moments and powers at the involved joints (van Ingen Schenau, G. J., 1990), it could imply, that in order to generate higher poling forces over a short time, it is necessary in a motor control perspective that the elbow joint flexes and the shoulder joint extends. Such coordination is highly skilled and regulated through bi-articular muscles, which tend to be active with often no relation to the actual angular velocity direction in the joints, which these muscles cross. Instead, during multi-joint movements, they distribute the net moments in the most effective way, so that a certain direction and magnitude of an external can actually be achieved. Thus, the high impact poling forces are absorbed and/or transported by the elbow joint to the shoulder joint through the bi-articular m. triceps brachii long head. This would be beneficial considering that the larger proximally located shoulder extensor muscles have a higher potential to generate work than the smaller distally located elbow extensors. However, more research is needed that combines kinematics and EMG with a mechanical approach to further the understanding of any possible SSC at the level of the elbow, shoulder or hip joints, and to further the understanding of other possible mechanisms, such as transport of power between the upper extremities joints during the DP locomotion.

Some differences between ergometer and treadmill or skiing DP should be mentioned. One obvious difference is the effect of increased intensity on relative PT. Although absolute PT decreased (0.62 s vs 0.49 s), the relative PT increased from MOD and HIGH to MAX (44.9% to 47.3%). This is opposite to treadmill DP, where relative PT decreased from 41% at low to 28% at maximal speed (Lindinger et al., 2009b). Thus, the absolute PT at high treadmill speeds is usually ~0.30 s (e.g., Holmberg et al., 2005; Lindinger et al., 2009a). The higher absolute and relative poling times in the present study mostly occur because of the increased air resistance in the ergometer flywheel, as force application is increased. This is important when interpreting the findings of the present study. For example, since the force application time is longer, rate of force development will be lower than when treadmill DP. This may have other effects on especially angular velocity of the joints, muscle activation (e.g. muscle force) and thus joint moments and powers. However, when comparing basic behaviour of joint kinematics, poling and ground reaction force over the cycle, these are generally in good agreement with studies on treadmill DP (Holmberg et al., 2005; Lindinger et al., 2009a; Lindinger et al., 2009b). Also, Linnamo et al. (2013) found significant longer relative poling times, using the same ergometer as in this study, when compared to treadmill DP. However, it was concluded that e.g. the muscle activation dynamics were very similar to treadmill DP.

Moreover, since the relative poling times is longer in ergometer DP compared to treadmill DP, this will likely affect the behaviour of P_{body} and also joint powers in the light of the SSC, as discussed above. That is, it might be that for example the change from negative to positive P_{body} occurs more rapid while treadmill DP, since the absolute poling times is lower and thus the flux in vertical $CoM_{(t)}$ will also occur faster. However, Nilsson, Tinmark, Halvorsen and Arndt (2013) investigated the effect of increased speed and horizontal resistance on several physiological and biomechanical parameters during treadmill DP. They found increased relative poling times in the latter, which was a way of simulating increased air resistance or ski-snow friction. This is important taking into account that during on-snow skiing, skiers often encounter conditions such as large ski-snow friction and/or wind resistance. Furthermore, during races skiers usually perform on flat or slightly uphill terrain, and at intensities comparable to HIGH in the present study (unpublished data). These findings likely have important practical applications to cross-country skiers and coaches. That is, one might be utilizing different DP strategies and coordination patterns depending on whether one is DP on an ergometer, roller skiing or on-snow skiing. More research with a mechanical approach is needed to further the understanding of different movement tasks during training or racing at different levels of incline, horizontal resistance, roller skiing or ergometer skiing.

In conclusion, the present study revealed that utilization of E_{body} is the main contributor to P_{poling}. Additionally, a significant effect of intensity was found on the relative contributions of the various joints to poling power. This was mostly due to the lower extremities significantly increasing its relative contribution by changing from absorbing to generating energy during poling phase. The lower extremities are also essential for the fluctuations in E_{body} over the DP cycle. The mechanical approach of the present study revealed important findings regarding coordination and fluctuations in energy within the different DP phases. However, more research with a mechanical approach is needed to further the understanding of cross-country skiing in general and DP in specific.

Acknowledgements

I would like to thank all the skiers and their coaches for their enthusiastic cooperation and participation in this study, and Xianchun Tan and Asgeir Rognstad for all their help in the lab. A special thanks to my supervisors Gertjan Ettema and Øyvind Sandbakk for an amazing learning process and very interesting discussions.

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