The Effect of Exercise Intensity on Joint Power and Dynamics in Ergometer Double-Poling Performed by Cross-Country Skiers

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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 ($p<0.001$), 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.

Keywords: Dynamic constraints; Power; Mechanical energy; Force; Cross-country skiing

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 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 et al. (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 $ml \cdot kg \cdot min^{-1}$) 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 DP) and measurement of external forces is extremely accurate.

All trials were performed with the participants standing on a force plate secured on the floor, wearing running shoes. In order to ensure that the participants maintained the same position in front of the ergometer, a steel plate was secured on the force plate in front of the feet at a distance from the ergometer that most closely simulated DP movements on snow or roller skiing (Halonen et al., 2015). All skiers were familiarized with DP on the ergometer, which was frequently used in their normal training routines.

For inter-individual comparisons, the skiers were instructed to perform the trials at rating of perceived exertion (RPE) values of ~10, ~13, ~16 and 20 at LOW, MOD, HIGH and MAX, respectively, on the Borg 6-20 scale (Borg, 1970). Accordingly, the participants generated external power outputs in relation to their own performance levels and body size. All participants had at least 6 yr experience in performing extensive endurance training and were considered experienced in subjective control of intensity. The integrated SkiErg performance monitor (PM4) displayed the mean DP power output delivered to the ergometer, allowing each subject to monitor and maintain the power output as stable as possible throughout the submaximal trials as instructed. MAX was performed at maximal sustainable effort, although the participants spent the initial ~10-20 s to attain a power production they deemed sustainable for 3 min. The participants performed all trials at their own freely chosen cycle rates.

2.3. Kinetic and kinematic measurements

Poling force (F_{poling}) was measured using a Futek Miniature Tension and Compression Load Cell (Futek LCM200, capacity 250 lb, non-linearity ± 0.5%, hysteresis ± 0.5%, weight 17 g, Futek Inc., Irvine, CA, USA) which was mounted in series with the drive cord inside the casing of the ergometer using a Rod End Bearing (Futek, GOD00730). The load cell was calibrated against a range of forces of known magnitude employing calibrated weights. GRF was measured by a Kistler force plate (Kistler 9286BA, Kistler Instrumente AG, Winterthur, Switzerland). All force data were sampled at 500 Hz.

Seven infrared Oqus cameras (Qualisys AB, Gothenburg, Sweden) captured three-dimensional position characteristics of passive, spherical reflective markers at a sampling frequency of 100 Hz. Four markers were fixed on the ergometer to measure the poling movement: two on the right and left handles and two on the right and left points where the ropes entered the ergometer. Two reference markers were placed on the force plate in order to describe the point of application of the GRF within the global coordinate system. Seven reflective markers were placed on the left side of the body (using double-sided tape; 3M, Maplewood, MN, USA) at the following anatomical landmarks: distal end of the fifth metatarsal (on the shoe), lateral malleolus, lateral femoral epicondyle, trochanter major, lateral end of the acromion process, lateral humeral epicondyle and ulnar styloid process. All force and movement data were recorded simultaneously and synchronized using the Qualisys Track Manager software (Qualisys AB). Offline data processing was done in MATLAB 8.1.0. (R2013a, Mathworks Inc., Natick, MA, USA).

2.3. Data analysis

Force and kinematic data were low-pass filtered (8th order, zero-lag Butterworth filter) cutting off at 50 and 25 Hz, respectively. Because there are no typical impact forces in the present setup, the use of different cut-offs for kinematics and kinetics had no impact on joint moment calculations as visually checked (e.g., van den Bogert & de Koning, 1996). Bilateral movement symmetry was assumed, so the position data of the left side of the body was assumed to be the average of left and right, and all data were analyzed in the sagittal plane. The sagittal plane limb segments were defined as foot, leg, thigh, trunk (including head), arm, and forearm (see Figure 1). Segment lengths were determined from marker coordinates and averaged over the entire period of analysis. Masses, moments of inertia, and center of mass of the segments were calculated using the anthropometric data according to de Leva (1996) and individual body mass and segment lengths. Linear and angular velocities and accelerations of the limb segments and the velocity of the poling handles relative to the ergometer were calculated by numerical differentiation of position data with respect to time. Instantaneous net joint moments were obtained using inverse dynamics by solving the equations of motion for a linked segment model (Elftman, 1939). For the ankle moment the GRF was the external force, while for the elbow moment F_{poling} was the external force (Figure 1). Extending joint moments and velocities (including plantar flexion) were defined positive. Joint power was calculated by multiplication of net joint moment and joint angular velocity.

Instantaneous P_{poling} was calculated as F_{poling} multiplied by the poling handle velocity. In DP locomotion considerable flexion and extension movements occur in the non-rigid trunk segment not modelled here, likely involving power. Due to the inherent problem in obtaining reliable net moment data about the non-rigid trunk, we used a rationale similar to e.g., Riddick and Kuo (2016) to account for power associated with trunk movements. According to the instantaneous power equation of van Ingen Schenau and Cavanagh (1990), at each instant in time, the sum of joint powers (P_j, the power source), derived from rigid body inverse dynamics, must equal the sum of the two possible power destinations; the time rate of change of E_{body} ($\dot{E}_{body}$) and the power that flows to the external environment (P_{poling}):

$$\sum_{j=1}^{5} P_j = \dot{E}_{body} + P_{poling} \qquad [1]$$

where P_j is the power at joint $_j$. However, because within-trunk movements were neglected in the inverse dynamics, any difference between P_j and $\dot{E}_{body} + P_{poling}$ was accounted for as trunk power:

$$P_{trunk} = \left(\dot{E}_{body} + P_{poling}\right) - \sum_{j=1}^{5} P_j \qquad [2]$$

$\dot{E}_{body}$ is:

$$\dot{E}_{body} = \frac{dE_{body}}{dt} \qquad [3]$$

E_{body} is the total body energy, calculated by summation across all 6 segments:

$$E_{body} = \sum_{i=1}^{6} E_i \qquad [4]$$

where E_i is the total energy of segment $_i$:

$$E_i = \frac{1}{2} m_i v_i^2 + m_i g h_i + \frac{1}{2} I_i \omega_i^2 \qquad [5]$$

where m_i is segment mass (kg), v_i is segment absolute velocity ($m \cdot s^{-1}$), g is gravitational acceleration (9.81 $m \cdot s^{-2}$), h_i is segment height above ground (m), I_i is segment moment of inertia ($kg \cdot m^2$), and ω_i is segment angular velocity ($rad \cdot s^{-1}$).

With the feet remaining on the ground at all times, and with only a simple set of pulleys between the load cell and movement registration, we assumed that power associated with friction was negligible. Finally, the moment generated about CoM by the reaction force of F_{poling} and the GRF, as well as their sum (net moment about CoM), was calculated.

One DP cycle was defined as from the shortest to the subsequent shortest length of the ropes. The poling phase was defined as from the shortest to the longest length of the ropes, and the recovery phase was defined as from the longest to the shortest length of the ropes. Poling time (PT) was defined as the duration of the poling phase, cycle time (CT) as the duration of an entire poling + recovery movement, relative PT as the percentage of CT, and cycle rate (CR) as the number of poling cycles per second.

All data, including joint powers (elbow, shoulder, hip, knee, ankle, and trunk), were time normalized and averaged over ~20 cycles for each subject at each of the intensities, and then averaged across subjects. Joint powers were averaged over the cycle, the PP, and the RP, separately for each participant. Relative joint power values were then calculated as the ratio of these average joint power values to cycle average P_{poling} ($P_{poling\text{-}mean}$).

2.4. Statistical Analysis

All data were checked for normality by visual inspection of normal Q-Q plots and histograms and are presented as means ± 95% CI. To determine the effect of intensity, one-way analysis of variance (ANOVA) with repeated measures for intensity was performed on each dependent variable (absolute and relative joint powers (averaged over the cycle, the PP and the RP), $P_{poling\text{-}mean}$, CR, absolute and relative PT, and relevant kinematic variables). For $P_{poling\text{-}mean}$, the difference contrasts were tested for significance to confirm that the protocol induced four different work intensities. Similarly, for RPE (reported as median ± IQR), a Wilcoxon rank tests was used to test for differences between adjacent intensities. Statistical significance was based on $\alpha = 0.05$ and all statistical tests were performed using SPSS version 24 (IBM Inc., Armonk, NY, USA).

3. Results

3.1. Basic cycle characteristics

All reported RPE values were close to target values (9 ± 3, 13 ± 1, 15 ± 2, 19 ± 0), and were significantly different between adjacent intensities ($p<0.01$). Ergometer DP at these intensities corresponded to $P_{poling\text{-}mean}$ of 116 ± 10, 166 ± 22, 214 ± 25, and 306 ± 25 W, which were significantly different between adjacent intensities ($p<0.001$). Note that the increase in $P_{poling\text{-}mean}$ was ~50 W between submaximal intensities and ~90 W between HIGH and MAX. CR increased (0.74 ± 0.06, 0.78 ± 0.06, 0.84 ± 0.07, and 0.97 ± 0.07 s^{-1}) and PT decreased (0.62 ± 0.04, 0.58 ± 0.03, 0.54 ± 0.03, and 0.49 ± 0.02 s) with intensity ($p<0.05$), while relative PT remained similar from LOW to HIGH (~45 ± 1%) and slightly increased from HIGH to MAX (~47 ± 1%; $p<0.05$).

3.2. Forces and kinematics

Across all intensities, F_{poling} as well as GRF showed very similar patterns (Fig 2A-C). In Fig. 2D and E a stick figure of one representative skier, including dynamics, is shown at LOW and MAX. In general, the gross movement pattern remained similar across all intensities, while the magnitude of forces and ranges of motion increased ($p<0.05$; Fig 3 A-J). Increasing intensity led to an increased within-cycle vertical fluctuation of CoM (Fig 2 D and E; $p<0.001$). Note that the minimum CoM height decreased more with intensity (~10 cm from LOW to MAX) than the maximum height increased (~3 cm from LOW to MAX). This pattern is reflected in hip - and knee joint angle range of motion (Fig. 3C, D). The shoulder mostly extended throughout the PP, while the elbow showed a distinct flexion-extension movement pattern (Fig. 3A, B). Since CR increased, almost all joint (mean flexion and extension) angular velocities increased with intensity ($p<0.05$; Fig. 3F-J).

3.3. Moments and powers

The moment about CoM caused by F_{poling} and the GRF are shown in Fig. 2F. During poling, the reaction force of F_{poling} tended to rotate the body backwards (i.e., acting in front of the CoM). This was opposed by a generally forward rotating effect of GRF (i.e., acting behind the CoM).

Across intensities, the net joint moments progressively increased (Fig. 3 K-O). Similarly, joint powers showed comparable patterns across all intensities, though progressively increasing in magnitude (Fig. 3 P-T) with one exception: at LOW and MOD a hip extensor moment occurred throughout the movement cycle, which changed into a flexor moment in the recovery-to-poling transition period at HIGH and especially MAX (Fig. 3 M). This is reflected in substantial positive hip power in the same time period (Fig. 3 R). Furthermore, the high peak extending moment and corresponding peak power at the hip in

MAX in the poling-to-recovery transition period are the clearest effects in accordance with the large power difference (~90 W) between HIGH and MAX.

Averaged absolute and relative joint powers are shown in Table 1. Over the entire cycle, most power was produced at the hip and shoulder at all intensities. Power at ankle, hip, shoulder and trunk increased ($p<0.001$) while elbow power decreased ($p<0.05$) with increasing intensity (Table 1). Relative hip power increased while relative shoulder power decreased ($p<0.001$). The contributions from ankle and elbow were rather small but still somewhat affected by intensity. Trunk contribution remained similar at ~13%. Lower body power (sum of ankle, knee and hip) amounted to ~37 ± 5%, ~39 ± 5%, ~43 ± 4% and ~54 ± 5% at LOW, MOD, HIGH and MAX, respectively. That is, the relative contribution from the lower body substantially increased with intensity ($p<0.001$).

During PP, the shoulder generated considerable power at all intensities (Table 1). Shoulder power rapidly increased to a (large) peak, coinciding with peak F_{poling} as well as with the peak in negative elbow power (Fig. 3P, Q). Elbow, trunk, and hip power were both positive and negative (Fig. 3P, R, U). Ankle power showed a distinct negative period during the beginning of PP (Fig. 3T). Knee power is negative and moderate at the first part of PP, its magnitude increasing with intensity (Fig. 3S). Averaged over PP, absolute hip and shoulder power increased considerably with intensity ($p<0.001$), and trunk power increased moderately ($p<0.01$). Relative hip power greatly increased (from ~0 to ~41%) from LOW to MAX ($p<0.001$), and relative shoulder power decreased (from ~88 to ~75%) somewhat from HIGH to MAX ($p<0.001$; Table 1). At submaximal intensities, mean elbow power was positive and contributed to $P_{poling\text{-}mean}$ (~10%), but became negative at MAX. Trunk contribution tended to increase with intensity ($p=0.090$).

In the RP no P_{poling} is generated and the sum of all instantaneous joint powers equals the positive rate of change in E_{body} (i.e., E_{body} increased as the body was heightened and repositioned; Figs. 2D and E). Here, most power was generated by the hip and ankle, followed by the trunk (Figs. 3R, T; Table 1). Small but significant effects of intensity were found for knee and hip relative power; hip relative power decreased from LOW to HIGH and then increased from HIGH to MAX (p=0.084; Table 1).

4. Discussion

The purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in DP locomotion, and the main question was whether the power contribution from the lower body joints over the movement cycle would decrease or increase when DP intensity was increased. Our findings show that increased $P_{poling\text{-}mean}$ was achieved by an increased contribution from the lower body joints, whereas the relative contribution from upper body joints decreased. This observation is in agreement with those of Bojsen-Møller et al. (2010), Rud et al. (2014) and Zoppirolli et al. (2016) who also demonstrated that increasing DP intensity was mainly done by increased lower body involvement. Somewhat surprisingly, the main increase in contribution by the lower body over the cycle occurred during PP, where hip contribution increased from ~0% at LOW to ~41% at MAX.

Since considerable (positive) work is done at the hip during PP, the idea that the lower body only does work during RP (Danielsen et al., 2015) is not supported. The substantial increase in positive hip power during PP found here may seem unexpected, but partly reflects that repositioning of the body starts prior to the end of PP and from a deeper position with increasing intensity, as found in roller skiing DP (Lindinger, Stöggl, et al., 2009). This is also reflected in an increasing amount of positive trunk power during the final part of poling; more hip and trunk (extensor) work is responsible for this task. Still, most of body heightening occurs during RP, where hip and ankle do most of the work. However, maximum CoM height does not increase much (Danielsen et al., 2015). Although the amount of absolute work involved in repositioning during RP increases, relative power does not increase. The increases in absolute hip and ankle power during recovery also reflect that this heightening occurs faster (as CR is increased). The only small positive knee power during the final part of poling and throughout recovery indicates that little knee work is directly associated with repositioning.

4.1. Dynamic constraints

When making inferences about joint powers, one must keep in mind that in all multi-joint movements, such as DP, a unique combination of joint moments are required to achieve certain magnitudes and directions of external forces, leading to a coordinated movement. These moments may demand positive, negative or zero joint power (Jacobs & van Ingen Schenau, 1992; van Ingen Schenau, 1989). In ergometer DP, these requirements are also determined by specific constraints, in that the skier must maintain dynamic balance and position on the floor. In our set-up, during PP, F_{poling} acts in front of the CoM, creating a backward rotating moment which (on average over a cycle) must be balanced by a forward rotating moment resulting from GRF that acts behind the CoM (Fig. 2E and F). This constraint is reflected in e.g., the negative ankle power during PP at all intensities, as a plantar flexing moment during dorsal flexion aids in obtaining a GRF that acts behind the CoM. The ankle moment and power found here seem to correspond well with the high activation levels of the triceps surae muscles during dorsal flexion in this phase in roller-skiing DP (Holmberg et al., 2005). The same applies for the hip power at onset of PP, but at this joint the net moment changes from extending to flexing with increasing intensity. This is reflected by the change in direction of the GRF, which at submaximal intensities acts just in front of the hip joint but at MAX acts behind (Fig. 2D and E). This in turn requires (small) negative power at submaximal, while at MAX considerable positive power is seen (and required) during the transition from RP to PP. A similar change occurred also in knee joint dynamics, but to a lesser extent. In general, generation of F_{poling} demands a particular direction of GRF (control of balance) which clearly has implications for coordination and therefore joint dynamics. Although kinematic patterns remain largely similar (though increasing in magnitudes, Fig. 3), some dynamics essentially change. In order to generate higher F_{poling} at increasing intensities, a larger GRF_x-GRF_y ratio seems required. This is partially brought about by reversed signs of hip and knee moments.

Overall, the effect of intensity on the kinematics of ergometer DP (Fig. 2 and 3) seem very comparable to roller skiing DP (Lindinger, Stöggl, et al., 2009). However, ergometer DP contains an additional degree of freedom compared to DP on roller skis or snow: ergometer DP allows for the use of horizontal frictional forces to regulate the direction of the GRF, which is not possible in roller- or on-snow skiing DP. Thus, in these latter conditions, the only way the skier can generate a moment arm for GRF about CoM is to adjust the vertical alignment between center of pressure and CoM. Alternatively, the angling and positioning of the poles is an option for control of rotational and dynamic balance, i.e., minimize the moment about CoM produced by F_{poling}. However, in general the F_{poling} vector is directed more downwards (on average) in ergometer DP than in roller- or on-snow skiing DP (more backwards through PP). Thus, effectively producing F_{poling} in these different modes of DP requires differences in coordination and joint dynamics. These mechanical dissimilarities between different modes of DP may cause differences in the solution to the requirements of dynamic constraints (control of balance and angular momentum) and in the way of achieving the mechanical goal, that is, effectively generating external power. Therefore, although the effect of intensity on the kinematics seems to be comparable between different modes of DP, this may not be the case for joint dynamics. In order to understand how these aspects may differ between DP modes, and possibly between skiers of different performance levels, future studies examining joint dynamics in on-snow or roller skiing DP as well as in skiers at different performance levels are required.

4.2. Energy flow and transfer

4.2.1. Lower extremity

During the onset of PP at MAX, when E_{body} is decreasing, the high positive hip power may reflect that the hip directly assists in generation of external power during flexion (pulling trunk down). Thus, the change from an extending to a flexing hip moment and the associated large increase in positive power is in accordance with a substantial increase in hip flexor muscle activity (Zoppirolli, Boccia, Bortolan, Schena, & Pellegrini, 2017). Otherwise, transfer of E_{body}, resulting from lower body work (in previous RP), is the main source of propulsion power during PP. This can best be understood by following the flow of mechanical energy from its source (muscle-tendon, joint power) to external work (P_{poling}) in ergometer DP: muscle-tendons in the lower body generate mechanical energy, mostly during RP, which increases the body energy. As the body then exerts force externally (F_{poling}) in PP, parts of E_{body} are transferred as the body performs this external work (e.g., Winter, 2009). In that regard, Danielsen et al. (2015) found a period of net energy absorption during the beginning of PP at submaximal intensities. This negative net (joint) work rate occurred simultaneously with high P_{poling}, suggesting that all P_{poling} originates solely from E_{body} with e.g., the upper extremities acting isometrically. This is clearly not the case: the shoulder immediately generates considerable power when F_{poling} increases (Fig. 3Q), meaning that both E_{body} transfer and active upper extremity muscle work drive propulsion immediately and simultaneously in ergometer DP. Moreover, the present analysis shows that, although the period of negative net muscle work is rather short (Danielsen et al., 2015), hip and knee power is negative also later into PP. The time point in which these powers change from negative to positive coincide with the change from trunk, hip and knee flexion to extension, that is, around the time point in which E_{body} has reached its minimum value and body heightening begins. These patterns remain similar at all intensities, and support the idea that some lower extremity muscles may be going through a SSC during this countermovement-like action (Danielsen et al., 2015). This SSC may allow reutilization of possible excesses of E_{body} (E_{body} not transferred to P_{poling}) which otherwise would be wasted, or potentiate muscle force production.

4.2.2. Upper extremity

Previous studies have hypothesized that a SSC may occur in shoulder and elbow extensors during PP, especially in the triceps brachii (Lindinger, Holmberg, et al., 2009; Zoppirolli et al., 2013). Although typical SSC kinematics and dynamics can be seen in the elbow (i.e., flexion-extension movement coinciding with negative-positive power), we found no such clear pattern for the shoulder. The situation concerning SSC is complicated because of possible energy transfer via bi-articular muscles between the shoulder and elbow. The triceps brachii contains a bi-articular part (caput longum) that is both a shoulder and elbow extensor. In multi-joint movements, bi-articular muscles are often active with no relation to the actual angular displacement of the joints crossed (e.g., van Ingen Schenau, 1989). However, they play an essential role in distributing the net moment and power about the joints in the most effective way (Jacobs & van Ingen Schenau, 1992; van Ingen Schenau, 1989). The coinciding peaks in negative elbow and positive shoulder power are an indication of power transfer between these joints (first half of PP, Fig. 3P-Q). This may allow for a distribution of power to the joints and muscle groups that are most suitable to do work (Bobbert & van Ingen Schenau, 1988). Considering DP, allowing for power transfer to the shoulder would be beneficial if we assume that the larger, more proximally located shoulder extensor muscle groups are more suitable to do most of the active work during PP, rather than the smaller, more distally located elbow extensors. Furthermore, ensuring that the upper arm and forearm rotate in opposite directions during this first part of PP has the benefit of decreasing joint angular velocity, which increases poling time and allows more muscle work to be done over a longer time period (e.g., Bobbert, Gerritsen, Litjens, & van Soest, 1996). This movement pattern is likely also essential for an effective transfer of E_{body} into P_{poling} ('fall on the ropes or poles').

Moreover, ergometer DP does not have a typical countermovement-like action at the upper limbs, since there is no braking force present (the ropes are continuously pulled downwards/backwards, immediately generating propulsion) with no rapid impact forces. This issue is one of the main differences from other typical bouncing-ball movements involving muscle-tendon SSC, such as running (see Danielsen et al., 2015). In skiing or roller skiing DP, however, high impact forces can occur as the poles hit the ground (e.g., Stöggl & Holmberg, 2016). Although some shoulder and elbow extensor muscle-tendons may be forcefully stretched by pole-ground impact, the poles are nevertheless angled slightly backwards (Stöggl & Holmberg, 2011). Hence, propulsion is immediately generated also here, without a typical braking period that would involve (elastic) storage of decreasing E_{body}, as in typical bouncing-ball movements involving muscle-tendon SSC (e.g., running). A rapid and immediate increase in F_{poling} from onset of poling, generating very high instantaneous P_{poling} in a rather short time, seems to be essential for DP performance in general (Holmberg et al., 2005; Lindinger & Holmberg, 2011; Lindinger, Stöggl, et al., 2009; Stöggl & Holmberg, 2011). The main mechanism allowing for such high propulsion power over a short poling time, increasing recovery time, seems to be the effective use of the legs as a major source of energy generation in the RP (Danielsen et al., 2015; Holmberg, Lindinger, Stöggl, Björklund, & Müller, 2006; Lindinger, Stöggl, et al., 2009), whereas DP relying only on arm or upper-body work drastically lowers power generation capability (Hegge et al., 2016). In the PP, a certain body configuration is necessary for effective transfer of this energy, as well as for generation of additional propulsion power through active (mostly upper extremity) muscle work. To achieve this, a coordination pattern allowing for power transfer between the elbow and shoulder (and between the body and propulsion power) may prevail over SSC in explaining the kinematics and dynamics of the upper extremities in particular. For the lower extremities, however, SSC may occur in the countermovement-like transition from body lowering to body heightening since this is an effective way of reutilizing otherwise wasted energy. Nevertheless, future studies should examine these concepts regarding joint – and whole body – dynamics in roller- and on-snow skiing DP.

4.3. Concluding remarks

Regarding the potential use of horizontal GRF, ergometer DP differs from roller- and on-snow skiing DP both uphill and on the level. This may have consequences for DP coordination and dynamics. Still, ergometer DP may resemble skiing DP on the level more than uphill because of the perpendicular orientation of the (virtual) goal directed movement in relation to gravity. As in ergometer DP, in level skiing the vertical and rotational energy fluctuations (making up the most of total E_{body}, Danielsen et al. (2015)) can be distinguished from external power (to be associated with forward kinetic energy). In contrast, when skiing uphill (above a certain gradient) the vertical energy fluctuations make up most of the external work done. Therefore, the utilization of E_{body}, i.e., the use of the lower body for mechanical energy generation, will be compromised in uphill DP. While intensity generally has an increasing effect on the relative power contribution of the lower body, if intensity is increased by going up a steeper incline, the mechanism may fail. The lower efficiency of DP on a steep incline (Dahl et al., 2017) is in accordance with this rationale. On the other hand, poling times in ergometer DP resemble uphill DP more than level DP (Stöggl & Holmberg, 2016). In level DP, poling time decrease considerably with increasing speed (intensity), reaching critically low values (~0.25 s) which has implications for coordination, mechanics and technique (Lindinger, Holmberg, et al., 2009; Lindinger, Stöggl, et al., 2009). Future studies are warranted that examine possible similarities and differences between different modes of DP.

In the present examination of ergometer DP, the lower body's relative power contribution to propulsive power rose substantially with increasing exercise intensity, as a result of enhanced relative hip power during the PP, but not in the RP. To increase E_{body} during repositioning, considerable power is generated in the RP (and at the end of PP) by lower body joints at all intensities. During PP, a transfer of E_{body} is the main source of propulsion power. However, this transfer drives propulsion simultaneously with active (mostly upper extremity) muscle work. At higher intensities, hip dynamics essentially changed, from that of mostly absorbing at LOW to generating considerable power within PP at MAX, which may also contribute directly to P_{poling}.

Finally, a SSC may possibly be involved in hip and trunk extensors in the countermovement-like transition from body lowering to heightening, likely involving reutilization of otherwise wasted E_{body}, or potentiate muscle force production. Considering the upper extremity during PP, our data suggest that certain kinematic and dynamic patterns are related more to power distribution and transfer concepts rather than a countermovement SSC mechanism.

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FIGURE LEGENDS

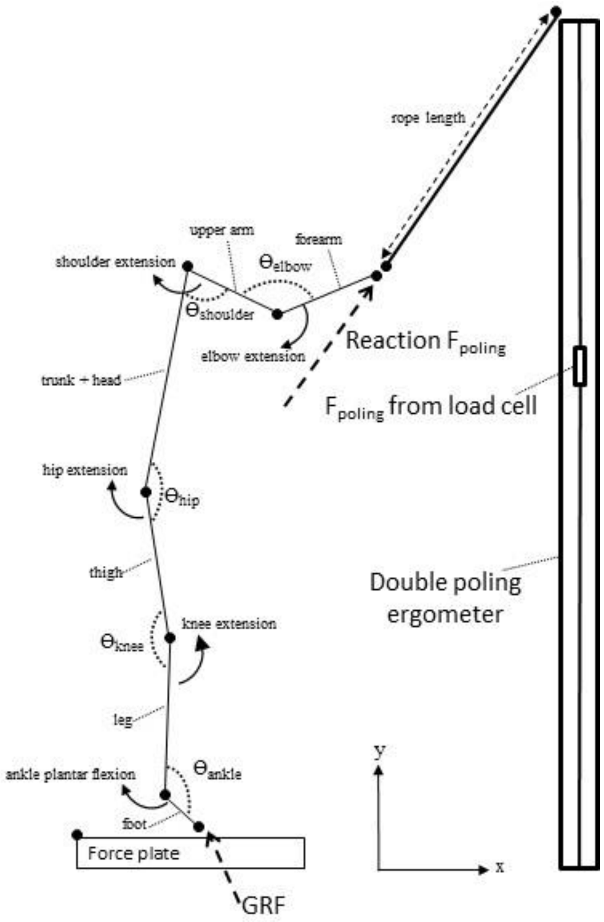
FIGURE 1. Illustration of marker placements (black dots), segments, definition of joint angles, and external forces.

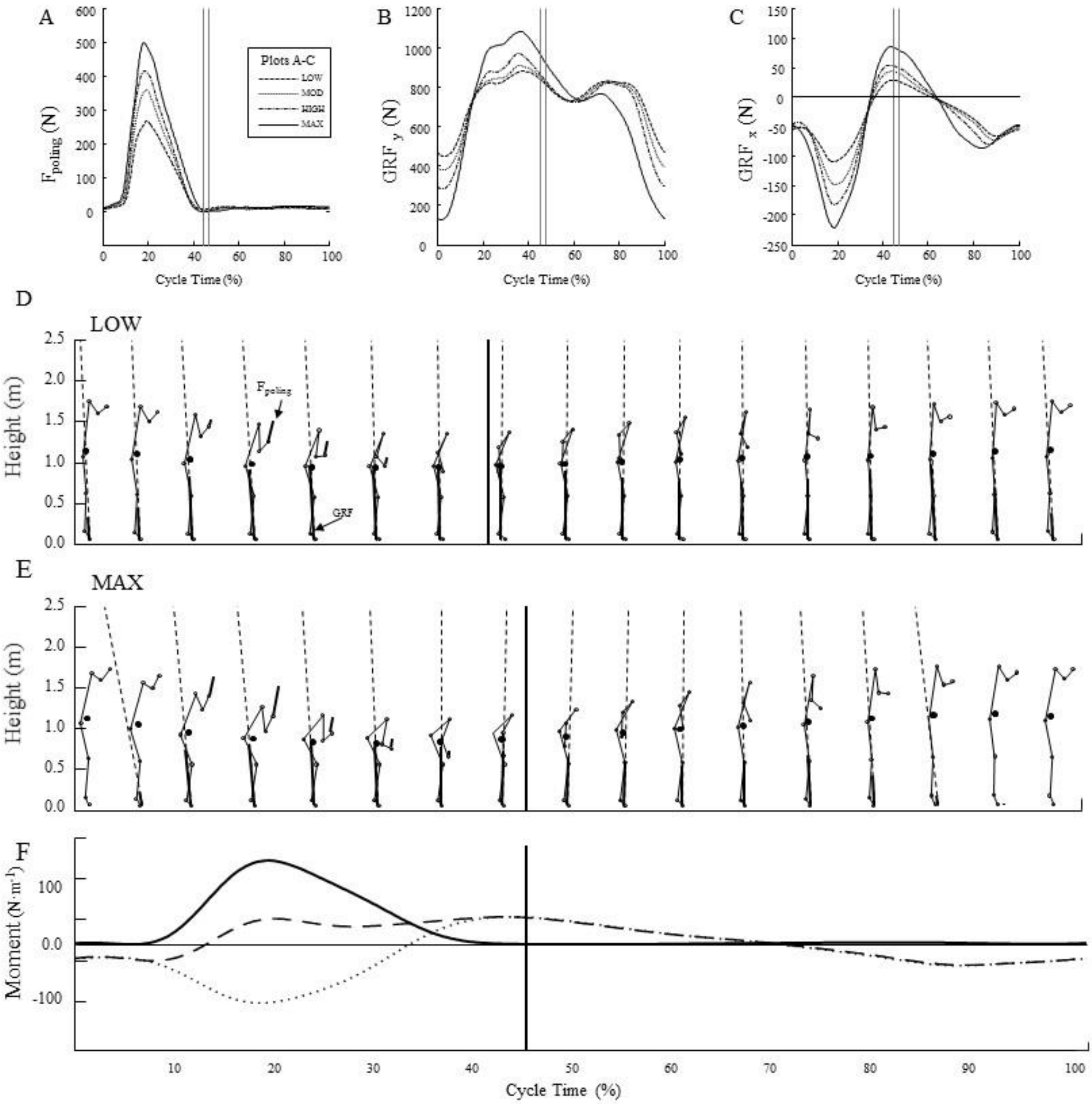
FIGURE 2. **A** Time trajectories of poling force (F_{poling}), **B** the vertical component of ground reaction force (GRF_y), and **C** the horizontal component of GRF (GRF_x). Values are the means over all subjects (N=9). The vertical lines represent end of poling phase. **D** and **E** Stickfigure of a typical example shown at different time points during an ergometer double poling cycle at intensities LOW (**D**) and MAX (**E**). The reconstruction of the GRF, the poling force (F_{poling}) and the CoM (black circle) are shown. The dashed GRF lines represent a magnification of the true GRF (solid black lines) to better illustrate its line of action. **F** Moment about CoM caused by reaction F_{poling} (solid line), the GRF (dotted line), and the net moment (dashed line), at intensity HIGH, mean of all subjects.

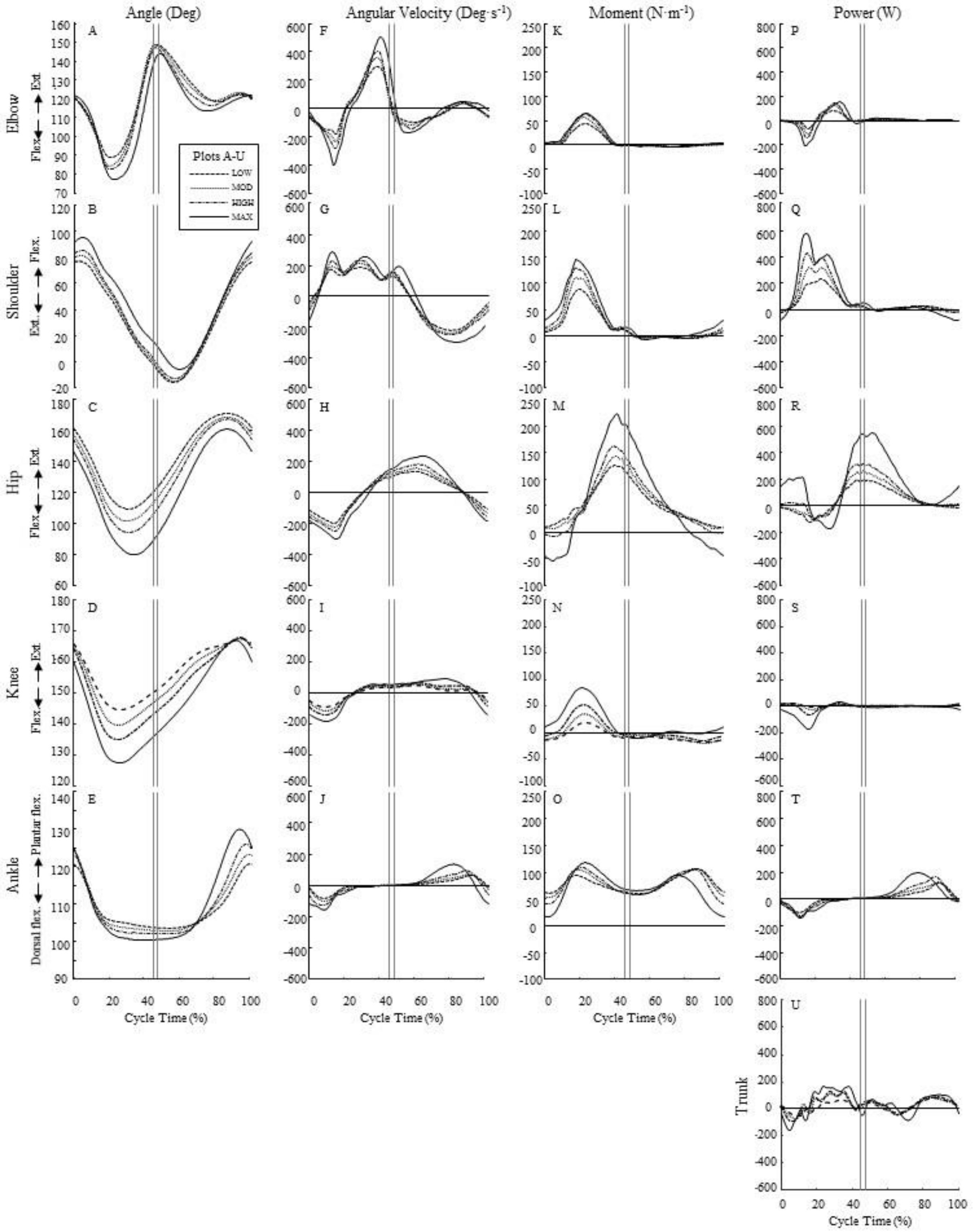
FIGURE 3. Mean curves of joint angles (A-E), joint angular velocities (F-J), net joint moments (K-O) and joint powers (P-U) plotted against normalized cycle time at the 4 intensities while ergometer double poling (N=9). The vertical lines indicate end of poling phase at submaximal (left) and maximal (right) intensities.

TABLE 1. Absolute (W) and relative (%) joint power (mean ± 95% confidence interval, *N*=9) while ergometer double poling at increasing intensities. A Joint power averaged over the cycle and their contribution to cycle average poling power ($P_{\text{poling-mean}}$). B Joint power averaged over the poling phase and their contribution to $P_{\text{poling-mean}}$. C Joint power averaged over the recovery phase and their contribution to $P_{\text{poling-mean}}$.

Intensity	Ankle	Knee	Hip	Shoulder	Elbow	Trunk
A Cycle						
LOW	6 ± 3 W	-2 ± 3 W	38 ± 7 W	52 ± 10 W	6 ± 6 W	15 ± 6 W
MOD	9 ± 4 W	-3 ± 4 W	58 ± 7 W	69 ± 13 W	8 ± 9 W	25 ± 12 W
HIGH	13 ± 6 W	-7 ± 4 W	84 ± 10 W	85 ± 17 W	7 ± 9 W	31 ± 10 W
MAX	22 ± 7 W	-20 ± 7 W	164 ± 16 W	104 ± 21 W	-1 ± 13 W	39 ± 12 W
	$F_{3,24}$=25, p<0.001	$F_{3,24}$=63, p<0.001	$F_{3,24}$=219, p<0.001	$F_{3,27}$=42, p<0.001	$F_{3,24}$=3.9, p=0.020	$F_{3,24}$=16, p=0.001
LOW	5 ± 2%	-2 ± 3%	33 ± 7%	45 ± 6%	6 ± 5%	13 ± 6%
MOD	5 ± 3%	-2 ± 2%	37 ± 8%	42 ± 6%	5 ± 5%	14 ± 6%
HIGH	6 ± 3%	-3 ± 2%	40 ± 5%	40 ± 6%	3 ± 4%	14 ± 5%
MAX	7 ± 2%	-7 ± 2%	54 ± 6%	33 ± 5%	0 ± 4%	12 ± 4%
	$F_{3,24}$=3.9, p=0.022	$F_{3,24}$=50, p<0.001	$F_{3,24}$=57, p<0.001	$F_{3,27}$=19, p<0.001	$F_{3,24}$=12, p<0.001	$F_{3,24}$=0.4, p=0.769
B Poling phase						
LOW	-33 ± 11 W	0 ± 4 W	0 ± 14 W	104 ± 20 W	12 ± 12 W	5 ± 13 W
MOD	-41 ± 13 W	-3 ± 3 W	19 ± 14 W	145 ± 30 W	16 ± 19 W	28 ± 26 W
HIGH	-46 ± 14 W	-11 ± 4 W	47 ± 18 W	185 ± 37 W	14 ± 21 W	29 ± 16 W
MAX	-45 ± 13 W	-40 ± 7 W	123 ± 26 W	232 ± 47 W	-7 ± 28 W	45 ± 26 W
	$F_{3,24}$=4.5, p=0.014	$F_{3,24}$=147, p<0.001	$F_{3,24}$=96, p<0.001	$F_{3,27}$=55, p<0.001	$F_{3,24}$=5.4, p=0.006	$F_{3,24}$=6.5, p<0.01
LOW	-28 ± 8%	0 ± 4%	0 ± 12%	88 ± 10%	11 ± 10%	5 ± 12%
MOD	-24 ± 8%	-2 ± 2%	11 ± 7%	87 ± 12%	10 ± 11%	15 ± 14%
HIGH	-21 ± 5%	-5 ± 2%	21 ± 7%	85 ± 11%	7 ± 10%	13 ± 8%
MAX	-14 ± 4%	-13 ± 2%	41 ± 8%	75 ± 11%	-2 ± 9%	14 ± 9%
	$F_{3,24}$=9.2, p<0.001	$F_{3,24}$=69, p<0.001	$F_{3,24}$=48, p<0.001	$F_{3,27}$=16, p<0.001	$F_{3,24}$=14, p<0.001	$F_{3,24}$=2.8, p=0.090
C Recovery phase						
LOW	39 ± 15 W	-4 ± 4 W	71 ± 17 W	10 ± 6 W	1 ± 1 W	24 ± 8 W
MOD	50 ± 19 W	-4 ± 5 W	90 ± 17 W	7 ± 7 W	2 ± 1 W	23 ± 13 W
HIGH	62 ± 22 W	-3 ± 7 W	116 ± 20 W	3 ± 8 W	2 ± 1 W	33 ± 15 W
MAX	83 ± 19 W	-3 ± 7 W	200 ± 35 W	-13 ± 9 W	4 ± 1 W	34 ± 18 W
	$F_{3,24}$=37, p<0.001	$F_{3,24}$=0.2, p=0.888	$F_{3,24}$=73, p<0.001	$F_{3,27}$=16, p<0.001	$F_{3,24}$=6.0, p=0.003	$F_{3,24}$=1.3, p=0.293
LOW	33 ± 11%	-3 ± 3%	62 ± 16%	8 ± 5%	1 ± 1%	20 ± 6%
MOD	29 ± 11%	-3 ± 3%	58 ± 17%	5 ± 4%	1 ± 1%	13 ± 6%
HIGH	28 ± 9%	-2 ± 3%	56 ± 12%	2 ± 4%	1 ± 1%	15 ± 6%
MAX	27 ± 5%	-1 ± 2%	66 ± 12%	-4 ± 3%	1 ± 0%	11 ± 6%
	$F_{3,24}$=1.5, p=0.252	$F_{3,24}$=3.5, p=0.030	$F_{3,24}$=2.5, p=0.084	$F_{3,27}$=16, p<0.001	$F_{3,24}$=0.8, p=0.509	$F_{3,24}$=2.8, p=0.100


rope length
upper arm
forearm
Θ_{elbow}
shoulder extension
$\Theta_{shoulder}$
elbow extension
Reaction F_{poling}
trunk + head
F_{poling} from load cell
hip extension
Θ_{hip}
thigh
Double poling ergometer
knee extension
Θ_{knee}
leg
y
ankle plantar flexion
Θ_{ankle}
foot
Force plate
x
GRF


A
B
C
Plots A-C
LOW
MOD
HIGH
MAX
F_{poling} (N)
GRF_y (N)
GRF_x (N)
Cycle Time (%)
600
500
400
300
200
100
0
1200
1000
800
600
400
200
0
150
100
50
0
-50
-100
-150
-200
-250
0
20
40
60
80
100
D
LOW
F_{poling}
GRF
Height (m)
2.5
2.0
1.5
1.0
0.5
0.0
E
MAX
Height (m)
F
Moment (N·m^{-1})
100
0.0
-100
10
20
30
40
50
60
70
80
90
100
Cycle Time (%)


Angle (Deg)
Angular Velocity ($Deg \cdot s^{-1}$)
Moment ($N \cdot m^{-1}$)
Power (W)
Elbow
Flex. ← → Ext.
Shoulder
Ext. ← → Flex.
Hip
Flex. ← → Ext.
Knee
Flex. ← → Ext.
Ankle
Dorsal flex. ← → Plantar flex.
Trunk
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
Plots A-U
LOW
MOD
HIGH
MAX
Cycle Time (%)
0
20
40
60
80
100