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RESEARCH ARTICLE

Gait models and mechanical energy in three cross-country skiing techniques

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ABSTRACT

Fluctuations in mechanical energy of the body center of mass (COM) have been widely analyzed when investigating different gaits in human and animal locomotion. We applied this approach to estimate the mechanical work in cross-country skiing and to identify the fundamental mechanisms of this particular form of locomotion. We acquired movements of body segments, skis, poles and plantar pressures for eight skiers while they roller skied on a treadmill at 14 km h^{-1} and a 2 deg slope using three different techniques (diagonal stride, DS; double poling, DP; double poling with kick, DK). The work associated with kinetic energy (KE) changes of COM was not different between techniques; the work against gravity associated with potential energy (PE) changes was higher for DP than for DK and was lowest for DS. Mechanical work against the external environment was 0.87 J m^{-1} kg^{-1} for DS, 0.70 J m^{-1} kg^{-1} for DP and 0.79 J m^{-1} kg^{-1} for DK. The work done to overcome frictional forces, which is negligible in walking and running, was 17.8%, 32.3% and 24.8% of external mechanical work for DS, DP and DK, respectively. The pendulum-like recovery (*R*%) between PE and KE was ~45%, ~26% and ~9% for DP, DK and DS, respectively, but energy losses by friction are not accounted for in this computation. The pattern of fluctuations of PE and KE indicates that DS can be described as a 'grounded running', where aerial phases are substituted by ski gliding phases, DP can be described as a pendular gait, whereas DK is a combination of both.

KEY WORDS: Locomotion, Mechanical work, Roller skiing

INTRODUCTION

Humans and other animals have developed different types of gait to travel at different speeds or through different environments. Humans usually travel by walking or running, whereas quadrupeds show three different forms of gaits, called walk, trot and gallop. Differences in gaits are characterized by particular kinematic features, such as the relative timing of the swing and stance phases during the entire stride (Biewener, 2006). As an animal moves over its supporting limb, the whole body position fluctuates with respect to the environment and these fluctuations require muscle work (Cavagna and Kaneko, 1977). Although the classical definition of mechanical work is based on the computation of the work performed by an explicit force, the knowledge of the forces involved in biomechanics is not always available. Therefore, the calculation of mechanical work based on the changes of body energy has been used in the study of human and animal locomotion (e.g. Saibene and Minetti, 2003). The mechanical work needed to move the body with respect to the environment has been called external work (W^*_{EXT}); it can be computed as the sum of the increments in mechanical energy of the center of mass of the whole body (COM) and is associated with the displacement of COM relative to the surroundings (Willems et al., 1995) (W_{EXT}) plus the work done on the environment (W_{ENV}), if any. When moving on a hard and non-slippery surface, as usually is the case in walking or running, and in the absence of wind, W_{ENV} is essentially zero (Lejeune et al., 1998). In contrast, moving by gliding or rolling on wheels requires the user to overcome frictional forces resulting in an additional external work (W_{FR}).

The energy involved in the fluctuations of position of COM can be divided into two parts, the energy for moving the COM (kinetic energy, KE) and the energy to raise the COM (gravitational potential energy, PE). The mechanical work done during locomotion can be minimized by limiting the amount of energy that is lost through the motions of the body during each stride by the transfer of body energy from one form to another (Cavagna and Kaneko, 1977). Two basic mechanisms have been identified during terrestrial locomotion of mammals and birds, as well as during human walking or running (Biewener, 2006). One mechanism operates by converting KE into PE (and vice versa) through an 'inverted pendulum' mechanism (Margaria, 1976). In this model PE and KE fluctuates in phase opposition, allowing an exchange between the two forms of energy, so that the net change in total COM mechanical energy is minimized. This mechanism is present in walking: when the limbs contact the ground the COM begins to decelerate, leading to a decrease in KE; at the same time, as the COM vaults over the supporting limb, it rises, leading to an increase in PE. During the second half of the limb support period, COM falls forward and downward and then PE is converted back into KE, similar to an inverted pendulum. Thus KE and PE fluctuate in anti-phase during the walking gait and it is possible to assume that much of the KE is converted into PE and vice versa.

A second mechanical model used by animals with legs to minimize energy expenditure during locomotion characterizes the running gaits and includes quadrupedal trotting and bipedal hopping (Biewener, 2006). During these gaits, the COM lowers and decelerates after the limb contacts the ground, consequently, both PE and KE decrease over the first half of the limb support period; and they increase again during the second half. PE and KE then fluctuate in phase and this does not allow a useful exchange between these two forms of energy. Part of the energy can, however, be stored as elastic energy during the first part of the support phase in the spring elements of the limbs, principally the tendons, ligaments and muscles, and is partially released during the second part of the support phase. This mechanism is referred to as a spring mass or bouncing ball model (Margaria, 1976).

Analysis of the mechanical energy fluctuations has been widely used in the studies investigating human walking or running

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List of symbols and abbreviations

CL	cycle length
COM	center of mass
CT	cycle time
DK	double poling with kick technique
DP	double poling technique
DS	diagonal stride technique
$\boldsymbol{g}$	gravitational acceleration
h_{COM}	vertical position of COM with respect to the reference system moving with the treadmill belt
KE	kinetic energy
LTT	absolute duration of leg thrust phase
LTT%	relative duration of leg thrust phase with respect to cycle time
M	body mass
PE	potential energy
PT	absolute duration of poling phase
PT%	relative duration of poling phase with respect to cycle time
R%	amount of energy that can be recovered by the pendular exchange between the kinetic and potential energies of the COM
$R(t)$	instantaneous recovery of mechanical energy by exchange between the kinetic and potential energies of the COM
RL	RL% absolute and rolling length, relative rolling length with respect to cycle length
RT	RT% absolute duration of rolling phase, relative duration with respect to cycle time
ST	absolute duration of leg swing
ST%	relative duration of leg swing with respect to cycle time
v_{COM}	velocity of the center of mass in the sagittal plane with respect to treadmill belt
v_{ski}	velocity of the roller ski along the direction of progression with respect to treadmill belt
W^*_{EXT}	positive work done to move the COM plus the work against the environment
W_{ENV}	positive work done on the environment (here we assume it is due to frictional forces only, and then it is equal to W_{FR})
W_{EXT}	positive work done to maintain the movement of the COM, it is the sum of the increments in (PE+KE)
W_{FR}	work done against rolling friction
W_{KE}	positive work done to accelerate the COM
W_{PE}	positive work done to lift the COM against gravity
α	slope of the treadmill
μ	coefficient of friction

(Cavagna and Kaneko, 1977; Willems et al., 1995; Saibene and Minetti, 2003) or animal locomotion (Ahn et al., 2004; Rubenson et al., 2004; Biewener, 2006), not only to estimate mechanical work done during locomotion, but also to identify the fundamental mechanisms that underlie terrestrial gait and to distinguish between different gait modes (Biewener, 2006). To our knowledge, few studies have analyzed fluctuations of COM and estimated mechanical work in cross-country skiing (Norman and Komi, 1987; Norman et al., 1989; Minetti et al., 2001; Nakai and Ito, 2011). Cross-country skiing is a form of locomotion performed with the use of passive locomotory tools, skis and poles, which allow travel on snow with a reduced cost of transport compared with walking and running (Saibene and Minetti, 2003; Minetti, 2004). The use of skis allows gliding for a great part of the gait cycle and propulsion is sustained by the combined action of arms and legs, leading to a substantial increase in the stride length. Cross-country skiing can then be viewed as a four limb locomotion gait, which is rather peculiar for humans for whom bipedal locomotion is predominant.

Classical cross-country skiing can be performed by using three main techniques: diagonal stride, double poling and double poling with kick (Smith, 1992; Bilodeau et al., 1992). Diagonal stride (DS) is performed by exerting force through the skis and poles; the arms and legs are moved in a coordinated pattern that resembles that of walking or running. Here, the push of one arm is performed along with the push of the contralateral leg. The propulsive action of the leg entails a stop in the motion of the ski and a rapid downward and backward movement of the leg that can be described as a backward kick. Double poling (DP) is performed with symmetrical and synchronous movements of both poles, the propulsive action of which is enhanced by a considerable trunk flexion and involvement of the legs is minimal (Holmberg et al., 2006). Double poling with kick (DK) is performed with a poling action similar to that described for DP, with an additional left or right leg kick. These techniques are characterized by differences in contributions from the lower and upper limbs, as well as in the timing and duration of the propulsive phases (Smith, 1992; Nilsson et al., 2004). DS is used mainly on moderate-to-steep uphill slopes, DP is selected for skiing on flat tracks and it is the preferred technique at high speeds and DK is mainly used for skiing on low-to-moderate slopes.

Determination of the mechanical power output in cross-country skiing was performed by Norman and colleagues (Norman et al., 1989) by accounting for changes in the sum of the kinetic, potential and rotational energy of 15 body segments. However, they analyzed only DS, did not describe fluctuations of PE and KE (or calculate the energy exchange) and did not take into account the work done against snow friction. Another study (Minetti et al., 2001) analyzed the exchange between PE and KE and calculated W_{EXT} for DS and DK. They concluded that DS resembles running and DK resembles walking, at least in some mechanical aspects. In a recent study conducted on roller skis in DS (Nakai and Ito, 2011), mechanical work was calculated as previously done by Norman and colleagues (Norman et al., 1989) by further adding the contribution of frictional force. These authors, however, estimated the amount of frictional force as if the progression were entirely done by rolling and as if the frictional force remained constant through the whole skiing cycle. They did not assess the fluctuations of PE and KE and their exchange.

Quantification of mechanical work for cross-country skiing could provide information reflecting the energy demands of each technique. In the present study, we hypothesized that the differences in movement pattern and propulsion between the three techniques would be reflected in differences in the fluctuation of mechanical energy associated with the movement of the body center of mass and with the work to overcome friction forces. In particular, we hypothesized that DP would require a greater work to overcome friction and for raising the body against gravity than the other two techniques. The first aim of our study was to characterize the different cross-country skiing techniques in terms of the fundamental gait patterns by analyzing fluctuations of the mechanical energy of COM. The second aim was to estimate the contribution of the different parts of the external mechanical work for each skiing technique.

RESULTS

Cycle phase parameters

Cycle time (CT) was found to be significantly shorter for DS with respect to DP and DK (Table 1). Poling time (PT) was found to last between 0.40 s and 0.42 s; even though ANOVA showed significant differences between techniques ($F_{2,14}$=3.813, P=0.048), no differences were found with the *post hoc* pair-wise test. DS showed the highest percentage of PT over the whole cycle (Table 1). Leg thrust time (LTT) duration was found to be 0.131±0.016 s for DS and 0.176±0.011 s for DK. As a result of the fact that only one leg executes a kick action during a skiing cycle in DK, LTT% was found to be significantly lower for DK than for DS (Table 1).

Table 1. Cycle phase parameters for three different cross-country skiing techniques

	DS	DP	DK	$F_{2,14}$	Significance
CT (s)	1.34±0.03[a]	1.43±0.11	1.55±0.07	15.74	$P<0.001$
PT%	30.1±1.7[a]	29.8±1.9	27.3±2.2	12.25	$P=0.001$
LTT%	9.6±1.3[a,c]	0.0±0.0[b]	5.7±0.4	344.7	$P<0.001$
RT%	47.4±1.7[a,c]	100±0.0[b]	78.6±1.8	3558.5	$P<0.001$
ST%	42.8±1.9[a,c]	0.0±0.0[b]	10.1±1.5	2703.6	$P<0.001$
CL (m)	5.22±0.12[a]	5.55±0.43	6.02±0.27	15.74	$P<0.001$
RL%	41.1±1.5[a,c]	100±0.0[b]	83.0±2.1	3678.45	$P<0.001$
SL%	58.9±1.5[a,c]	0.0±0.0[b]	17.0±2.1	3678.45	$P<0.001$

Values represent means ± s.d. for all participants. *F*-values for repeated-measures ANOVA and its significance are reported.

CT, cycle time; PT%, LTT%, RT% and ST% represent the poling time, leg thrust time, rolling time and leg swing time expressed as a percentage of CT; CL, cycle length; RL% and SL% represent the distance traveled during rolling and swing phases, respectively, expressed as a percentage of CL.

[a]Pair-wise significance differences between techniques ($P<0.01$) for DS versus DP; [b]DP versus DK; [c]DS versus DK.

The rolling length (RL) was found to be significantly different between techniques both in the absolute values (DS, 2.13±0.11 m; DP, 5.55±0.43 m; DK, 4.63±0.64 m for one leg performing the kick and 5.38±0.78 m for the other leg) and in the percentage values (RL%, Table 1) covering the whole skiing cycle for DP and a lower percentage of the cycle for DK and DS. For DP, the rolling phase covers the whole cycle length (CL; Table 1); for DK, most of the cycle length is covered by rolling and only a minimal part by leg swinging. In contrast, for DS, most of the distance traveled during a skiing cycle is covered by leg swinging, with rolling contributing only 41.1% of CL.

Mechanical energy fluctuations

For DS, the fluctuations of KE and PE appear mainly in phase (Fig. 1). In this technique two minima, for both KE and PE, can be found immediately before each of the two kick actions; two subsequent energy increments in both KE and PE can be observed in correspondence to the left leg and right leg thrust phases (Fig. 1 and supplementary material Movie 1) that are characterized by the extension of the kicking leg. The time course of the recovery within the cycle $R(t)$ is null for most of the cycle (Fig. 1), it increases during the recovery of one leg before each kick action of the contralateral leg and during a very short time period at the beginning of each kick action, where KE is still decreasing and PE is already increasing because of the lift of COM as a result of the leg extension. The curves for W_{FR} show positive values during the rolling phase, as expected (Fig. 1, bottom panel).

For DP, the fluctuations of KE and PE are in phase opposition, with the minimum of PE corresponding approximately to the maximum of KE; both are located in the last part of the DP action (Fig. 2). During the poling action the KE curve rises and the PE curve decreases because of a pronounced flexion of the trunk. PE increased after the end of the poling action until the beginning of the subsequent poling action (supplementary material Movie 2). In the DP technique, the recovery curve $R(t)$ shows non-null values for most of the cycle (Fig. 2). The curves of W_{FR} for DP are quite constant, with higher values at the end of the poling phase, where KE is maximal (Fig. 2, bottom panel).

The fluctuations of the energies for DK are similar to those seen for DP during the first part of the skiing cycle, although of reduced amplitude. The fluctuations of KE and PE are in phase opposition during the first half of the cycle. During the second part of the cycle, in correspondence with the right leg kick (Fig. 3 and supplementary material Movie 3), KE shows a decrease and then a rapid increase, similar to that observed during the leg kick for DS, which is accompanied by a slight decrease and a subsequent increase of PE giving a local in-phase fluctuation pattern. The decrease in KE before and during the first part of kick action is probably due to the fact that the ski stops to perform the kick action (see Materials and methods). For DK, the trend of $R(t)$ (Fig. 3) resembles that of DP during the first part of the cycle, where the poling action occurs. Two sharp peaks occur before and at the beginning of the kick action, as seen for the kick actions during DS. The curves of W_{FR}

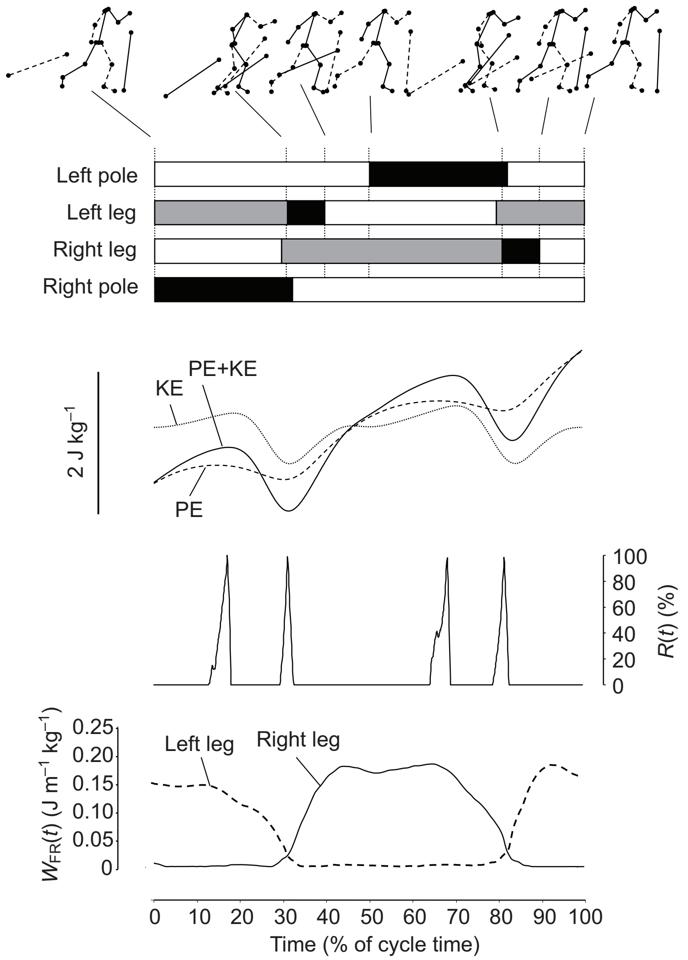

Fig. 1. Stick figures and main parameters for diagonal stride (DS) cross-country skiing. Stick figures show important cycle events (right side, solid line; left side, dashed line) (see also supplementary material Movie 1). The bar diagram represents timing of ski and pole phases (gray, rolling phase; black, propulsive phase; white, swing phase). The $R(t)$ curve indicates the time course of recovery. The bottom panel depicts work done against friction W_{FR}. The curves were obtained by time normalizing and averaging data from 12 consecutive cycles for subject 6.

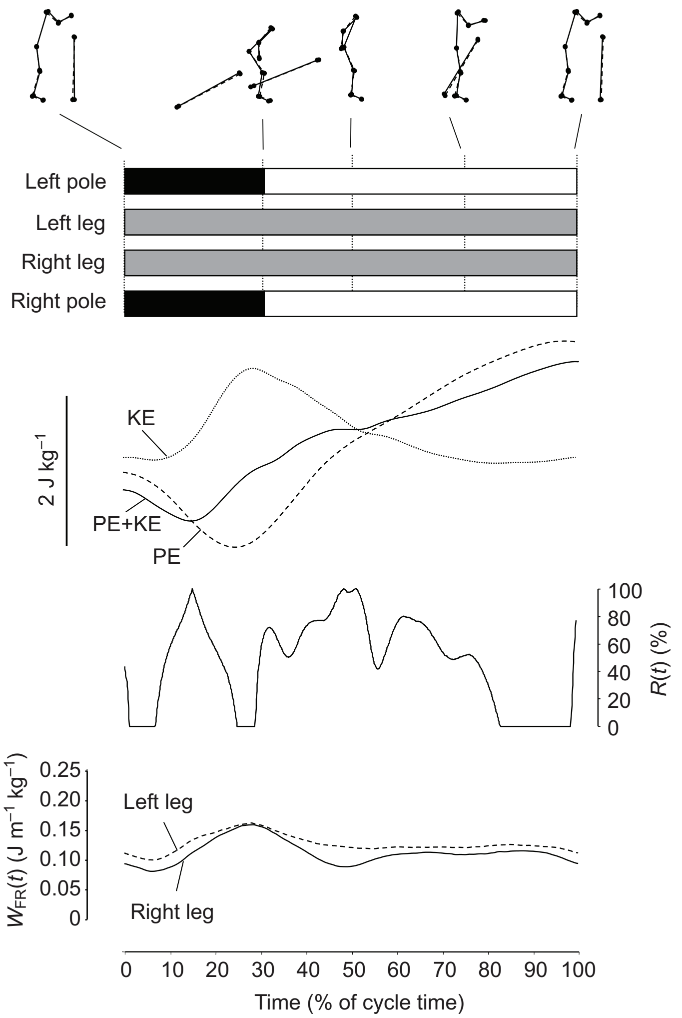

Fig. 2. Stick figures and main parameters for double poling (DP) cross-country skiing. Stick figures show important cycle events (right side, solid line; left side, dashed line) (see also supplementary material Movie 2). The bar diagram represents timing of ski and pole phases (gray, rolling phase; black, propulsive phase; white, swing phase). The $R(t)$ curve indicates the time course of recovery. The bottom panel depicts work done against friction W_{FR}. The curves were obtained by time normalizing and averaging data from 12 consecutive cycles for subject 6.

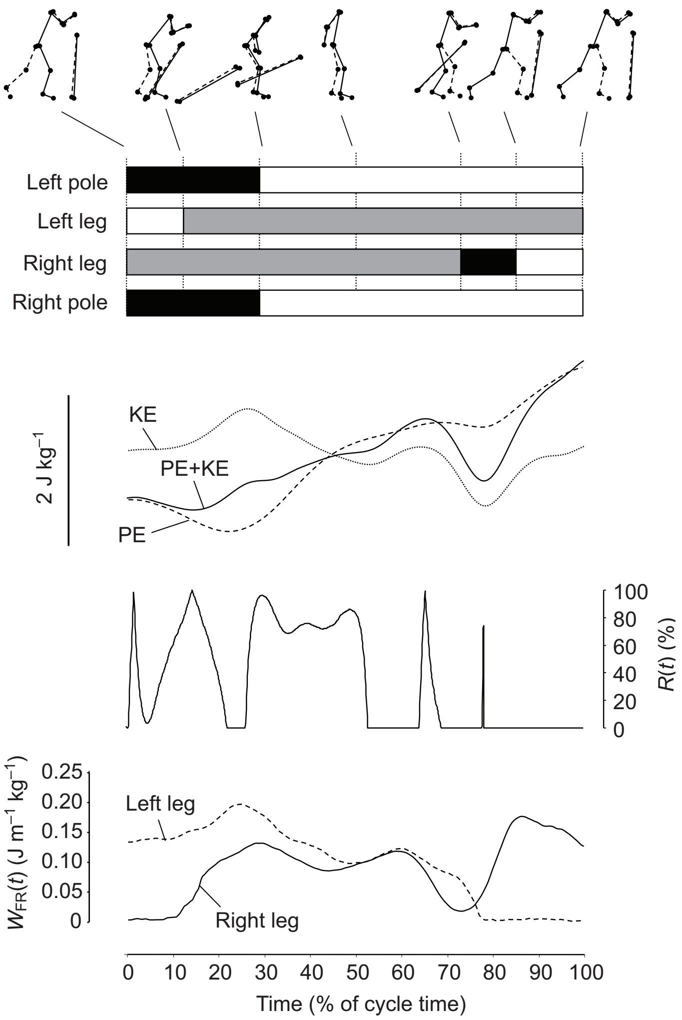

Fig. 3. Stick figures and main parameters for double poling with kick (DK) cross-country skiing. Stick figures show important cycle events (right side, solid line; left side, dashed line) (see also supplementary material Movie 3). The bar diagram represents timing of ski and pole phases (gray, rolling phase; black, propulsive phase; white, swing phase). The $R(t)$ curve indicates the time course of recovery. The bottom panel depicts work done against friction W_{FR}. The curves were obtained by time normalizing and averaging data from 12 consecutive cycles for subject 6.

for left and right leg for DK are non-null where the respective ski is rolling.

Mechanical work

The mechanical work associated with the increments of KE (W_{KE}) showed no differences between the three techniques (Table 2). On the contrary, the mechanical work associated with the increments in potential energy (W_{PE}) was found to be significantly higher for DP than for DK and DS. On average, the percentage energy recovery (R%) was significantly different between techniques, with DP showing the maximum value and DS the minimum one (Table 2). The work necessary to sustain increments of body COM energy (W_{EXT}) was lower for DP than for DK and DS, with DS showing the highest value, about 51% higher than that found for DP. The values of W_{FR} were significantly different between techniques: 26.3% and 31.4% lower for DK and DS, respectively, compared with DP. The values of W_{FR} were 17.8%, 32.3% and 24.8% of the values of W^*_{EXT} for DS, DP and DK, respectively. The values of W^*_{EXT} were significantly lower for DP with respect to DS and DK, with no differences between DS and DK.

DISCUSSION

As hypothesized, the three cross-country skiing techniques analyzed in the present study were found to be characterized by differences in the pattern of fluctuation of all the mechanical energy forms investigated, reflecting differences in the timing of propulsive actions. Differences in loading and rolling speed for roller skis result in different work required to cope with friction forces. Cycle timing analysis showed that DS is characterized, at the speed and slope analyzed in this study, by the shortest cycle and by the longest duration of overall propulsive actions, with respect to DK and DP techniques. The timing of the events in the gait cycle is different between techniques, with the propulsive action being distributed along the whole skiing cycle for DS and in contrast, concentrated in the first third of the cycle during DP. An intermediate situation was observed for DK that is characterized by the poling action in the first

Table 2. Mechanical work values for three different cross-country skiing techniques

	DS	DP	DK	$F_{2,14}$	Significance
W_{KE} (J m^{-1} kg^{-1})	0.329±0.065	0.291±0.014	0.305±0.027	1.711	P=0.216
W_{PE} (J m^{-1} kg^{-1})	0.457±0.039^{a}	0.575±0.028^{b}	0.502±0.042	48.47	P<0.001
W_{EXT} (J m^{-1} kg^{-1})	0.718±0.051^{a,c}	0.475±0.039^{b}	0.596±0.044	59.23	P<0.001
W_{FR} (J m^{-1} kg^{-1})	0.155±0.011^{a,c}	0.226±0.005^{b}	0.196±0.019	56.682	P<0.001
W^*_{EXT} (J m^{-1} kg^{-1})	0.873±0.048^{a}	0.701±0.040^{b}	0.792±0.050	26.122	P<0.001
R%	8.6±2.9^{a,c}	45.1±3.5^{b}	26.2±2.2	372.16	P<0.001

Values represent means ± s.d. for all participants. F-values for repeated-measures ANOVA and its significance are reported.
[a]Pair-wise significance differences between techniques (P<0.01) for DS versus DP; [b]DP versus DK; [c]DS versus DK.

third of the cycle and by the kick action nearly at the end of the cycle. Temporal variables are in accordance with results reported in previous studies that analyze similar speed conditions on both roller skis (Hoffman et al., 1995b) and on snow (Nilsson et al., 2004).

The duration and distribution of the propulsive actions are reflected in the fluctuation of the mechanical energies. The potential energy, in particular, shows a unique and broader oscillation of COM corresponding to the flexion-extension action of the trunk, which occurs during the poling phase of DP; on the contrary, DS shows two smaller fluctuations for each skiing cycle, which correspond to the two-leg push-offs. Despite the fact that skiing with the DS technique requires raising the COM twice during each cycle, the lower amplitude of the potential energy fluctuations results in a lower mechanical work with respect to DP. The amplitude of trunk flexion and extension performed to complete the poling phase in DP implies a deep rise and fall of body COM and makes this technique the most expensive in term of mechanical work against gravity.

The values of the recovery index, accounting for the possible exchange between PE and KE, were non-null for all techniques, indicating that at least part of the mechanical energy could be conserved within the cycle. We calculated that this energy-saving mechanism could be more effective for DP than for DK and it is the lowest for DS. Therefore, although skiing with DS requires lower vertical fluctuations of COM with respect to DK and DP, the low possibility of energy exchange may lead to higher overall mechanical work to sustain the movement of body COM for this technique.

Within-step analysis showed that the energy exchange between PE and KE can occur mainly during the flexion and extension of the trunk, corresponding to the poling and recovery actions, respectively, in both DP and DK. Energy exchange could also take place, even though to a minor extent, in DS and DK during leg swing, where COM accelerates and lowers, and during the earlier phase of kick, where COM decelerates and lifts. It is important to point out that, unlike in running and walking, in skiing, a non-negligible part of the energy of the system is dissipated by friction. Because friction was not taken into account in the calculation of R%, estimates of the energy exchange in skiing are necessarily incomplete. The dissipation of energy due to friction would lead to a lower pendulum-like transfer of energy with respect to that calculated for R% and this effect is greater when dissipation of friction is higher.

The analysis of the time course of PE and KE has been widely used in locomotion analysis to define the characteristics of gait in humans as well as in animals (Griffin and Kram, 2000; Ahn et al., 2004; Genin et al., 2010). The gaits are typically categorized into walking and running and can be distinguished using the phase relationship between PE and KE, as well as on the basis of other parameters, such as the duty factor (Hoyt et al., 2006) and the shape of the vertical ground reaction force profile (Biknevicius et al., 2004). These methods proved to be useful when identifying walking and running gaits in mammals, birds and lizards (Cavagna et al., 1977; Full and Tu, 1990; Muir et al., 1996; Hutchinson et al., 2003; Rubenson et al., 2004). The presence of an 'in-phase' relationship between PE and KE has been used to define the 'running gait' and to model it into a bouncing ball or pogo-stick paradigm (Cavagna et al., 1977) in humans (Margaria, 1976) and other mammals, birds, reptiles and insects (Cavagna et al., 1988; Hutchinson et al., 2003; Ahn et al., 2004; Biewener, 2006; Biancardi et al., 2011). A bouncing gait, as commonly found in birds and elephants is not necessarily associated with the existence of an aerial phase, even at fast speeds, and it is sometimes called 'grounded running' (Full and Tu, 1990; Hutchinson et al., 2003). It can be observed in humans when running with bent knees ('Groucho running') (McMahon et al., 1987) or at very low speed, mainly in old men (Cavagna et al., 2008) and may also have been present in pre-modern humans (Schmitt, 2003). We observedin-phase oscillation of PE and KE and a low value of R% for DS skiing and we can thus define DS skiing as a form of 'grounded running', where instead of the aerial phases of running, rolling phases can be observed.

In contrast, for DP, PE and KE are mostly in phase opposition and R% values are comparable to those typically found in level walking (Cavagna et al., 1976) and recently shown for uphill walking (up to 15% gradient) (Gomeñuka et al., 2014). The walking gait has been classically described by an inverted pendulum or rolling egg paradigm (Margaria, 1976), where the COM shows an inverted pendular motion given by the hips vaulting on the standing foot. For DP, we hypothesized that the pendular motion of the COM is given by the rotation of the trunk in the sagittal plane occurring with the flexion-extension motion performed during poling and recovery. Poling action causes an increase of KE and this action requires a flexion of the trunk that causes a concurrent decrease of PE until the end of this phase. During the first part of the recovery phase, a high value of $R(t)$ indicates that some KE may be used to lift the COM; however, part of this energy is likely dissipated by friction, resulting in a lower energy transfer than that calculated by R%. The energy curves of COM in DK are a combination of the patterns discussed for DP and DS, because in the first part of the cycle, PE and KE curves are out of phase, with high recovery values and with shapes resembling those observed in DP; in the second part of the cycle, corresponding to the kick action, the shape of the curve is similar to that of DS. Pendular and bouncing behaviors are thus both present in DK in different phases of the cycle.

To our knowledge, only one study has analyzed the PE and KE time course and recovery index in skiing (Minetti et al., 2001); they reported a value of R% for DK lower than that reported in this study and a comparable value for DS. However, the study of Minetti and colleagues was conducted on snow, at a higher speed for DK and at a higher slope for DS. As a practical implication, we observed that both beginners and expert skiers often believe that the DS technique is more similar to walking than to running, probably because of the absence of aerial phases. We suggest that an awareness of the similarity of DS with running, as far as the body COM motion is concerned, could help beginners in learning the correct technique.

The mechanical work in cross-country skiing is usually approximated by calculating the net change in center of mass height required to ascend a hill plus the work done against friction, which is considered to be constant through the skiing cycle and independent of technique (Hoffman et al., 1995b; Sandbakk et al., 2010; Nakai and Ito, 2011; Pellegrini et al., 2011; Sandbakk et al., 2012). To correctly calculate the work performed against friction, the rolling friction coefficient, the distance traveled by the roller skis while they are rolling and the perpendicular force loading each roller ski should be measured. In the majority of the studies reported so far, however, the work done against friction has been estimated as if the progression was entirely in gliding or rolling and as if the frictional force remained constant through the whole skiing cycle and was itself determined by considering the whole body weight (Hoffman et al., 1995b; Sandbakk et al., 2010; Nakai and Ito, 2011; Pellegrini et al., 2011). Sandbakk and colleagues (Sandbakk et al., 2012) recently improved the estimation of friction workload for roller ski skating by considering that the distance traveled by the skis is higher than the average distance traveled by the skier, because of the orientation of the skis with respect to the direction of the progression. Moreover, they took into account the idea that part of the body mass does not load the roller skis because it is applied on the poles. However, they estimated average and not instantaneous values of frictional forces over the skiing cycle and did not take into account the fact that during some phases a higher than average force could be exerted with a small or no ski displacement, yielding a low or null contribution to frictional work. Moreover, they did not take into account the existence of a swing phase in which the ski moves but is not in contact with the ground, (Bilodeau et al., 1992; Nilsson et al., 2004; Stöggl et al., 2008) so that part of the ski cycle is not subjected to frictional forces. We demonstrated in our investigation that, whereas for DP the skis are never lifted from the ground (thus the whole distance is covered by rolling on skis), only 41% of total distance traveled for DS and 83% for DK is covered by rolling. We found that the frictional work for DS and DK, calculated by considering the instantaneous values of speed and load on the skis, is 68% and 86%, respectively, of that for DP. Friction thus has a lower influence on DS and DK than on DP and this observation could justify the choice to change from DP to DK or DS when the friction coefficient increases. The knowledge of the influence of friction on the external mechanical work in skiing could allow estimation of the benefits of improving ski gliding properties in the different techniques.

It must be pointed out that roller skiing is not a perfect model for snow skiing (Dillman and Dufek, 1983; Hoffman et al., 1995a) and this could constitute a limitation of our study. On skis, many factors (such as snow and air temperature, and the quality of grooming) largely affect frictional forces and the reproducibility of the data (Hoffman, 1992). Working on a treadmill is a convenient solution, as it permits maintenance of a constant speed, slope and frictional force. For these reasons, the majority of the cross-country skiing studies published in the last 10 years have been performed on a treadmill. The biomechanical differences between roller skiing on the ground and skiing on snow (Dillman and Dufek, 1983; Baumann, 1985) seem to be attributable to differences in friction (Hoffman et al., 1995a). The coefficient of friction measured in our study (μ=0.024) is comparable to that reported when roller skiing on a treadmill by others (Kvamme et al., 2005; Hoffman et al., 1998; Sandbakk et al., 2010; Sandbakk et al., 2012) whereas the friction coefficient for skiing on snow can vary between 0.02 and 0.10 (Colbeck, 1994): similar to our value or up to five times larger. It can thus be calculated that the work against friction can be as large as 50% (DS), 81% (DP) and 62% (DK) of the total external work (for μ=0.10) compared with the 17%, 32% and 24% percentages found in this study (μ=0.024).

The calculation of mechanical work of skiing accounting for slope, average speed and friction reflects only a fraction of the total amount of mechanical work performed by the skier to sustain his/her locomotion with respect to the surroundings. Indeed, by neglecting the calculation of the within-cycle COM displacements and speed fluctuations, the external work is underestimated, at the speed and the slope of the present study, by 82%, 73% and 66% for DP, DK and DS, respectively.

It is important to point out that we calculated external mechanical work according to the work-energy principle, based on the PE and KE changes during a cycle. The values obtained by this procedure depart from the classical definition of work of a real force and reflect the work of an imaginary force acting at the COM (Zatsiorsky, 2000). In this framework, if both positive and negative energy changes are taken into account, the work for locomotion, within a gait cycle, is null (the ‘zero work paradox’); by considering only the positive changes of PE and KE it is therefore assumed that no energy is expended to perform negative work (Zatsiorsky, 2000). This assumption is not completely correct: because the efficiency of negative work is about five times larger than that of positive work (Abbott et al., 1952), negative work contributes ~20% to total metabolic cost. Even though neglecting the negative work contribution leads to an underestimation of the mechanical work and to metabolic cost estimates, this procedure has been used in several studies on terrestrial locomotion (Willems et al., 1995, Saibene and Minetti, 2003, Rubenson et al., 2004).

A further part of the total mechanical work performed by a subject in a locomotion task is the work needed to move the segments with respect to COM – the so-called internal work – which was not calculated in the present study. The only study that calculated internal work for cross-country skiing (Minetti et al., 2001) reported a value between 16% and 20% of the overall total work. Calculation of this quantity requires researchers to make assumptions (quite debated in the literature) on the possible transfer of energy between adjacent segments and between segments and COM (Kautz and Neptune, 2002). Further studies should thus investigate the contribution of internal work to total mechanical work in cross-country skiing.

The difference between the methods reported in the literature to calculate roller skiing workload accounting for slope, average speed and average friction and the one proposed in this study is mainly due to the fact that we took into account the contribution of fluctuations of the position and speed of COM and, to a lesser extent, that we calculated with better accuracy the work done against friction. If we do not take into account the fluctuations of COM position and speed, we obtained a parameter that represents the minimum work needed to accomplish the locomotion task. This parameter has been introduced for walking [W_{env} (Lejeune et al., 1998)] and for cycling [W_{bike} (Minetti, 2011)]. This ‘amount of work’ is entirely given by the external constraints of gravity and friction, and it is independent of the technique adopted and by the technical execution of the task. The two last components, technique and technical execution, determine the COM pattern of energy, so that the work necessary for changes in COM is strongly dependent on them. The ratio between the mechanical work effectively performed by the skiers to accomplish the task using a certain technique and the minimum work required by external constraint can then be considered to be a parameter reflecting skiing efficiency, similar to the so-called pedaling efficiency defined by Minetti for cycling (Minetti, 2011). Improving the economy of skiing may thus depend on the ability of the skier to reduce the mechanical work related to execution of the technique, which is associated with the COM position and speed fluctuations.

MATERIALS AND METHODS

Data were collected from eight male elite cross-country skiers. The height and body mass of the subjects (means ± s.d.) were 178.1±3.9 cm and 72.9±5.2 kg, respectively, and average age was 21.9±2.8 years. The study was pre-approved by the local Institutional Review Board and all subjects were fully informed about its nature, prior to providing their written consent to participate.

The measurements were performed using roller skis on a motorized treadmill with a belt surface 2.5 m wide and 3.5 m long (RL3500E, Rodby Innovation AB, Vänge, Sweden). All athletes used the same pair of Nord roller skis (Ski Skett, Sandrigo, Italy) whereas poles were available at lengths in multiples of 2.5 cm, so that each athlete could choose his preferred pole length. The treadmill belt consisted of a non-slip rubber surface. The coefficient of rolling resistance on the treadmill surface was determined from measurements of the force required to tow a skier standing still on the roller skis used during the test, as described in a previous study (Pellegrini et al., 2011).

All participants were familiar with the use of roller skis on the treadmill as part of their training and testing program and were secured with a safety harness connected to an emergency brake. Prior to testing, participants were allowed to warm up for 8 min by skiing at low intensity using all three techniques (DS, DP and DK). For data collection, a slope of 2 deg and a speed of 14 km h^{-1} were selected as a good compromise to perform either the techniques used for high slope and slow speed, and those used mainly for flat and high speed skiing. The slope was in line with that selected for roller skiing investigations by other researchers (Mittelstadt et al., 1995; Sandbakk et al., 2012; Holmberg et al., 2005; Lindinger et al., 2009b; Stöggl et al., 2007; Vähäsöyrinki et al., 2008). The order of the techniques was randomized for each subject. The participants were asked to ski for 3 min for each technique and the data were collected for 30 s during the last minute to allow the movement pattern to stabilize.

Pole force was measured using a lightweight single-axial load cell (Deltatech, Sogliano al Rubicone, Italy) mounted inside standard poles (Diamond Storm 10 Max; OneWay, Vantaa, Finland). Analogue signals from the force transducer were sampled at 200 Hz by means of a data acquisition board (NI DAQ-PAD-6016, 16 bit; National Instruments, Austin, TX, USA). The force transducers were dynamically calibrated before each test, as described in a previous study (Pellegrini et al., 2011).

Vertical plantar ground reaction forces were obtained at 100 Hz using a system consisting of two pressure distribution insoles, each with 99 capacitive sensors (Novel, Munich, Germany). Force data derived from pressure and area values of each sensor. Calibration of the insoles was performed prior to testing according to the manufacturer's instructions.

Body center of mass (COM) was determined from the position and the mass of body segments plus skis and poles. Kinematic data were obtained at 200 Hz by using an optoelectronic motion capture system (six cameras, MCU240, ProReflex; Qualisys, Göteborg, Sweden). The body was considered to be divided into 11 rigid segments: the head plus trunk, two upper arms, two lower arms, two thighs, two shanks and two feet. Reflective hemispheric markers were positioned on both sides of the body on the gleno-humeral joint, the lateral condyle of the humerus, the dorsal wrist, the great trochanter, the lateral condyle of the femur, the lateral malleolus and the fifth metatarsal phalangeal joint. Each segment mass and center of mass position was taken from Dempster's anthropometric tables (Dempster and Gaughran, 1967). Two markers were attached on each ski, one 2 cm before the binding and the other 2 cm behind the anterior wheel. Two reflective markers were positioned on each pole; one was placed 40 cm from the top of the pole and the other was placed 60 cm above the tip of the pole. The position of the center of mass of poles and rollers skis was determined as the position where a fulcrum maintained the objects in equilibrium. Position data for each marker were low-pass filtered with a fourth-order, zero phase-shift, low-pass Butterworth filter with a cut-off frequency of 15 Hz. Data collection was triggered by a digital signal in order to ensure synchronization between pole force, plantar force and kinematic data.

Calculation of biomechanical parameters

For all techniques, the beginning of each cycle was considered to be the right pole ground contact and the end was the subsequent right pole ground contact (Pellegrini et al., 2011; Holmberg et al., 2005; Lindinger et al., 2009a). Pole contact and pole take-off were identified from the force data, as the first point above and the first point below a force threshold of 10 N, respectively. We verified that this threshold is the minimum force value above the level of typical noise recorded during the recovery phase (Pellegrini et al., 2011). We calculated the duration of the poling action, poling time (PT), as the time between pole ground contact and pole take-off. Because the propulsive action of the leg can occur only when the ski stops with respect to the ground (Nilsson et al., 2004), we calculated leg thrust time (LTT) as the time period during which the ski was still (Bellizzi et al., 1998; Pellegrini et al., 2013). We calculated the speed of the roller skis (v_{ski}), with respect to the treadmill belt, as the speed along the direction of progression of the marker placed 2 cm in front of the ski binding. We identified 'ski stops' as the time during which v_{ski} remained below a threshold of 0.5 km h^{-1}. No ski stops were identified for the DP technique because no kick action is performed in this technique. Rolling time (RT) was considered as the time between the contact of the roller ski on the ground, detected as the first point above a plantar force threshold of 10 N, and the start of the leg thrust phase (Bilodeau et al., 1992). We calculated swing time (ST) by subtracting the duration of leg thrust and rolling to cycle time ST=CT–RT–LTT. All durations were expressed in absolute values and as a percentage of CT. We calculated the cycle length (CL) as the distance traveled by the COM during a skiing cycle, by multiplying the treadmill velocity by CT. We calculated the displacement of the roller skis along the direction of progression during the rolling and swing phases, rolling length (RL) and swing length (SL), respectively, by integrating v_{ski} over the rolling and swing phase, respectively. The values for RL and SL were averaged between left and right side and were expressed in absolute values and as a percentage of CL (RL% and SL%).

Calculation of mechanical work

The mechanical work for human and animal locomotion can be estimated based on the changes of the COM energies, according to the work-energy principle (Cavagna and Kaneko, 1977). We determined the kinetic ($\mathrm{KE}=0.5Mv^2_{\mathrm{COM}}$) and potential ($\mathrm{PE}=M\boldsymbol{g}h_{\mathrm{COM}}$) energy of COM by measuring v_{COM} (the instantaneous velocity of COM in the sagittal plane with respect to a reference system moving at the treadmill belt speed), h_{COM} (the height of COM in the vertical direction with respect to the origin of a reference system moving at the treadmill belt speed) and by knowing M (body mass) and $\boldsymbol{g}$ (the gravitational acceleration). We assumed that COM movements in classical cross-country skiing are mainly on the sagittal plane, therefore we did not considered the mediolateral COM velocity. We calculated W_{EXT} as the sum of positive increments of the summation of potential and kinetic energy (PE+KE) (Willems et al., 1995). We defined the positive external mechanical work while moving on roller skis W^*_{EXT} as the sum of the work needed to move COM (W_{EXT}) and the work needed to overcome rolling friction W_{FR}.

We quantified the degree of the possible energy exchange between PE and KE by calculating the percentage recovery of mechanical energy, R%, which accounts for how much energy can be saved through a pendulum-like locomotion (Cavagna et al., 1977) as:

$$R\% = \frac{W_{\mathrm{PE}} + W_{\mathrm{KE}} - W_{\mathrm{EXT}}}{W_{\mathrm{PE}} + W_{\mathrm{KE}}} \cdot 100\,. \tag{1}$$

This coefficient characterizes only a necessary but not sufficient condition for energy transfer since it neglects the transfer between other forms of energy (e.g. the frictional energy losses between ski and snow would lead the energy transfer to be less than calculated). We also calculated the percentage recovery at each instant of the cycle $R(t)$ based on the absolute values of positive and negative increments of mechanical energy at each time instant (t), as proposed by Cavagna and colleagues (Cavagna et al., 2002):

$$R(t)=\frac{\left|W_{\mathrm{PE}}(t)\right|+\left|W_{\mathrm{KE}}(t)\right|-\left|W_{\mathrm{EXT}}(t)\right|}{\left|W_{\mathrm{PE}}(t)\right|+\left|W_{\mathrm{KE}}(t)\right|}\cdot 100\,. \quad (2)$$

We determined the work to overcome roller ski friction (W_{FR}) as the integral over time of the product of frictional forces ($F_F=\mu Fp$, where μ is the coefficient of rolling friction and Fp the plantar force) and roller ski displacement along direction of progression. Calculation was done for left and right and summed up.

Finally, we normalized all energies for unit of body mass, we calculated all works over each complete cycle and we expressed the work per meter of distance traveled. All data were processed using Matlab 7.0 (MathWorks, Natick, MA, USA) and Excel 2003 (Microsoft, Redmond, WA, USA).

Statistical analysis

For each subject, the data resulted from the average of 12 consecutive cycles. The normality of the data was checked with the Shapiro–Wilk test. All parameters were analyzed to check for the statistical significance between techniques by means of ANOVA for repeated measures. A *post hoc* Bonferroni correction test was applied to analyze the differences between each pair of techniques. The assumption of sphericity was checked with the Mauchly's test. The level of significance was set at an α-value of $P<0.05$. SPSS 15.0 for Windows was used for all statistics.

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Competing interests

The authors declare no competing financial interests.

Author contributions

B.P., C.Z. and P.Z. formulated the study; B.P., C.Z. and L.B. conducted the experiments and analyzed the data. All the authors prepared and edited the manuscript.

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Supplementary material

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