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RESEARCH ARTICLE

Forces and mechanical energy fluctuations during diagonal stride roller skiing; running on wheels?

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ABSTRACT

Mechanical energy can be conserved during terrestrial locomotion in two ways: the inverted pendulum mechanism for walking and the spring–mass mechanism for running. Here, we investigated whether diagonal stride cross-country roller skiing (DIA) utilizes similar mechanisms. Based on previous studies, we hypothesized that running and DIA would share similar phase relationships and magnitudes of kinetic energy (KE), and gravitational potential energy (GPE) fluctuations, indicating elastic energy storage and return, as if roller skiing is like 'running on wheels'. Experienced skiers (*N*=9) walked and ran at 1.25 and 3 m s^{-1}, respectively, and roller skied with DIA at both speeds on a level dual-belt treadmill that recorded perpendicular and parallel forces. We calculated the KE and GPE of the center of mass from the force recordings. As expected, the KE and GPE fluctuated with an out-of-phase pattern during walking and an in-phase pattern during running. Unlike walking, during DIA, the KE and GPE fluctuations were in phase, as they are in running. However, during the glide phase, KE was dissipated as frictional heat and could not be stored elastically in the tendons, as in running. Elastic energy storage and return epitomize running and thus we reject our hypothesis. Diagonal stride cross-country skiing is a biomechanically unique movement that only superficially resembles walking or running.

KEY WORDS: Locomotion, Biomechanics, Cross-country skiing, Nordic skiing

INTRODUCTION

Aerial and aquatic locomotion often involve power–glide cycles. For example, zebra finches use flap–glide cycles, rather than steady, repetitive flapping, and this reduces the bird's cost of transport (Tobalske et al., 1999). Scallops and squid are well-known examples of aquatic animals that propel themselves forward using power–glide cycles (Marsh et al., 1992; O'Dor, 2013). Because the water intake and jet velocity are in the same direction, little energy is wasted with each push forward (Alexander, 2003). Also notable are water strider insects that use a rowing stroke of their middle legs, propelling themselves and then gliding along the surface. This row–glide cycle allows water striders to reach speeds of 150 cm s^{-1} (Hu et al., 2003). However, to our knowledge, the only example in nature of power–glide terrestrial locomotion is the 'tobogganing' gait of penguins. Tobogganing penguins lie on their bellies and, with alternating foot movements, push themselves along the ice and snow surfaces. Penguins appear to save energy by tobogganing as opposed to walking (Wilson, 1991). Thus, power–glide locomotion can be efficient, rapid and conserving of energy.

In contrast to power–glide locomotion, legged terrestrial locomotion generally involves evenly spaced, sequential foot–ground collisions. Terrestrial locomotion, i.e. walking and running, can also be mechanically economical. Walking and running use different mechanisms for alternately storing and recovering energy within a step and thereby reduce the need for muscular power input (Cavagna et al., 1977). These two mechanisms inherently rely on the braking and propulsion of the body during the repeated collisions with the ground. Through the use of passive tools (wheels, skates, skis), humans have enhanced muscle-driven locomotion (Minetti, 2004). By eliminating the repetitive collisions with the ground, such passive tools allow for terrestrial power–glide gaits. But do these enhanced forms of locomotion retain the same energy-saving mechanisms utilized in walking and running?

In this paper, we examined the fundamental center of mass (COM) mechanics of the classic diagonal stride form of human cross-country skiing (DIA). Diagonal stride cross-country skiing seems like it might be a hybrid form of locomotion, combining aspects of power–glide mechanics with terrestrial locomotion mechanisms of energy exchange, storage and return. The alternating arm and leg motion of DIA appears similar to walking at slow speeds and running at faster speeds but with a distinctive gliding phase. Indeed, in pioneering studies using kinematic analysis, Minetti et al. (Minetti et al., 2000) and Pellegrini (Pellegrini, 2011) skillfully surmised that DIA is biomechanically like running, at least in some respects. Before proceeding, it is important to consider what mechanically defines walking and running.

Kinematically, walking is defined as a gait in which the COM is highest at mid-stance during single leg support and lowest during periods of double support (McMahon et al., 1987). The cyclical lifting and lowering of the COM throughout each stance phase allows walking to utilize an inverted pendulum mechanism of energy exchange. In bipedal walking, kinetic energy (KE) and gravitational potential energy (GPE) of the COM fluctuate out of phase (Cavagna and Kaneko, 1977; Farley and Ferris, 1998). After heel strike, as the COM vaults up and over the stance leg, KE is converted into GPE. In the second half of the stance phase, GPE decreases and is converted into KE. This mechanism reduces the need for the muscles to perform all of the mechanical work involved. As a result of exchanging out-of-phase KE and GPE, walking is a mechanically economical mode of locomotion.

In contrast, during level running, KE and GPE fluctuations of the COM are in phase. Because the KE and GPE decrease and increase together, there is little exchange of energy between these two forms. Rather, in running the KE and GPE of the COM are converted into elastic energy. Theoretically, all of the mechanical energy of the COM can be stored elastically in the tendons and then recovered (Cavagna, 1977). Ker et al. (Ker et al., 1987) empirically demonstrated using human cadavers, that in human running the

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List of abbreviations

DIA	diagonal stride skiing
DIA NP	diagonal stride skiing with no poles
COM	center of mass
FTM	force measuring treadmill
GPE	gravitational potential energy
KE	kinetic energy
% BW	percentage bodyweight

Achilles tendon and arch of the foot alone stores more than half of the total COM energy fluctuations. Roberts et al. (Roberts et al., 1997) showed that, in running turkeys, the gastrocnemius muscle fascicles exhibit only small length changes while the tendon stretches and recoils. They reported that 'elastic energy recovery from the tendon…accounted for more than 60% of the work during shortening'.

Traditionally, running has been defined as a gait having an aerial phase during which no limbs are in contact with the ground. However, in some situations, humans and other species can exhibit grounded running, which is a bouncing gait that lacks an aerial phase (McMahon et al., 1987; Rubenson et al., 2004; Chang and Kram, 2007). Thus, perhaps a better definition of running is a gait during which the COM is lowest during mid-stance (McMahon et al., 1987) and elastic energy storage and return are utilized.

In this study, we asked, are the COM mechanics of diagonal stride cross-country skiing just like walking and/or running but with an additional gliding phase? Or, do the COM mechanical energy fluctuations of DIA constitute a unique gliding gait? Based on previous reports (Minetti et al., 2000; Pellegrini, 2011), we hypothesized that running and DIA share similar phase relationships and magnitudes of KE and GPE fluctuations, indicating elastic energy storage and return. In other words, we expected that roller skiing would be like 'running on wheels'. To test this hypothesis, we investigated the biomechanics of DIA on roller skis using a force-measuring treadmill (FTM) and compared walking, running and DIA at the same speeds in the same subjects.

RESULTS

The observed patterns and magnitudes of ground reaction forces for walking and running were typical (Fig. 1A,B). Walking exhibited two perpendicular force (F_{perp}) peaks, one after heel strike attaining ~105% of bodyweight (% BW) and then another during toe-off equal to ~100% BW. In walking, the parallel force (F_{par}) signal had a negative braking peak and a positive propulsive peak, averaging −13 and 14% BW, respectively.

Six of our nine subjects ran with a heel strike pattern, and their F_{perp} displayed two peaks. The initial impact peak for heel strikers had an average force of 145%, and the second or 'active' peak, which occurred at mid-stance, averaged 218% BW. Three subjects ran with a mid-foot strike pattern, and their F_{perp} only had one peak (active peak). As expected, the patterns of running F_{par} were similar to those of walking, comprising a negative braking peak and a positive propulsive peak. The averaged magnitudes of the peak braking and propulsive forces for running were −22% BW and 18%, respectively.

The vertical forces during each stride of diagonal stride roller skiing with (DIA) and without poles (DIA NP) (Fig. 1C,D) comprised five general phases, as identified previously (Vähäsöyrinki et al., 2008). A skiing stride was defined here as starting with (1) a pole plant followed by (2) a glide phase of the ipsilateral roller ski. Next, there was (3) a preload phase when the F_{perp} decreased, as the COM was lowered, in preparation for (4) the kick, when the ipsilateral roller ski pushed off the treadmill (5) as the contralateral roller ski moved forward into the glide phase. Note: we only could discern the preload (phase 3) in the individual force traces of highly skilled skiers, and preload was not apparent in averaged force traces (Fig. 1). This sequence of force patterns was apparent in DIA NP (Fig. 1C) and DIA (Fig. 1D), although DIA NP obviously did not involve a pole plant force.

The peak kick F_{perp} values recorded for DIA NP at 1.25 and 3 m s^{-1} averaged 91 and 119% BW, respectively with corresponding values for DIA of 86 and 100% BW, respectively. The peak kick force in the parallel direction (F_{par}) for DIA NP was 7.1% BW at 1.25 m s^{-1} and 12.5% BW at 3 m s^{-1}. The F_{par} of DIA (Fig. 1D) indicated propulsive peaks associated with both pole contact and kick (1.1 and 2.4% BW, respectively, at 1.25 m s^{-1} and 2.9 and 4.0% BW at 3 m s^{-1}, respectively). From the pole only measurement configuration, it was possible to determine the contribution of the poling force to DIA (Fig. 1E). The pole F_{perp} at 1.25 m s^{-1} and 3 m s^{-1} had peaks of 6.6 and 10.0% BW, respectively, and the F_{par} peaked at 2.3 and 6.2% BW, respectively.

The ground reaction forces of walking, running and skiing can be easily compared at matched speeds (Fig. 1A–D). The peak F_{perp} in DIA NP and DIA were less than running because there is no aerial phase in DIA NP and DIA, and also less than the walking F_{perp} at 1.25 m s^{-1}. The most important difference between walking, running and roller skiing was the very small negative, or braking, forces during the glide phases of DIA NP or DIA. These forces were of course due to the rolling of the roller skis themselves, which allowed the skiers to glide through the initiation of the contact phase, rather than abruptly decelerating the body similar to that in walking and running.

Fig. 2 depicts the mechanical energy fluctuations of the COM [KE, GPE and total energy (TE)], as calculated from the ground reaction forces. As has been well established, the mechanical energy fluctuations of the COM while walking have an out-of-phase pattern; the minimum KE occurred at 31.3% of the stride and the maximum GPE at 29.6% (Fig. 2). The phase difference (α) between the minimum KE and maximum GPE in walking was 11.7 deg. Owing to these nearly opposite, or out-of-phase energy fluctuations, the total COM energy, TE (=KE+GPE), for walking fluctuated by only 0.21 J kg^{-1} (Table 1). DIA NP and DIA at 1.25 m s^{-1} exhibited more in-phase fluctuations of KE and GPE; the KE minimum occurred at 45.3% of the stride at the initiation of the kick and the maximum GPE at 20.7% (Fig. 2). The calculated α of DIA NP at 1.25 m s^{-1} was 176.9 deg, which was significantly different to that for walking ($P<0.001$). The TE during DIA at 1.25 m s^{-1} fluctuated by 0.30 J kg^{-1}, whereas the corresponding value for DIA NP was 0.74 J kg^{-1} (Table 1).

Fig. 2 shows the COM mechanical energy fluctuations for running. As expected, the KE and GPE fluctuations were in phase. For running, KE reached a minimum during mid-stance at 17.8% of the running stride, and GPE was maximum at 41.9%. The phase difference in running was −173.7 deg. The TE of the COM during running fluctuated by 1.48 J kg^{-1} (Table 1). At 3 m s^{-1}, DIA NP also exhibited in-phase fluctuations of KE and GPE, with the maximum KE and minimum GPE at 50.9% and 26.9% of the stride, respectively. We calculated the phase difference to be 171.7 deg and as a result, the TE fluctuation was substantial, averaging 0.73 J kg^{-1} for DIA NP (Table 1). The phase differences calculated for both speeds of DIA NP were not significantly different from that of running ($P=0.95$), confirming that all three have in-phase fluctuations of the mechanical energies of the COM.

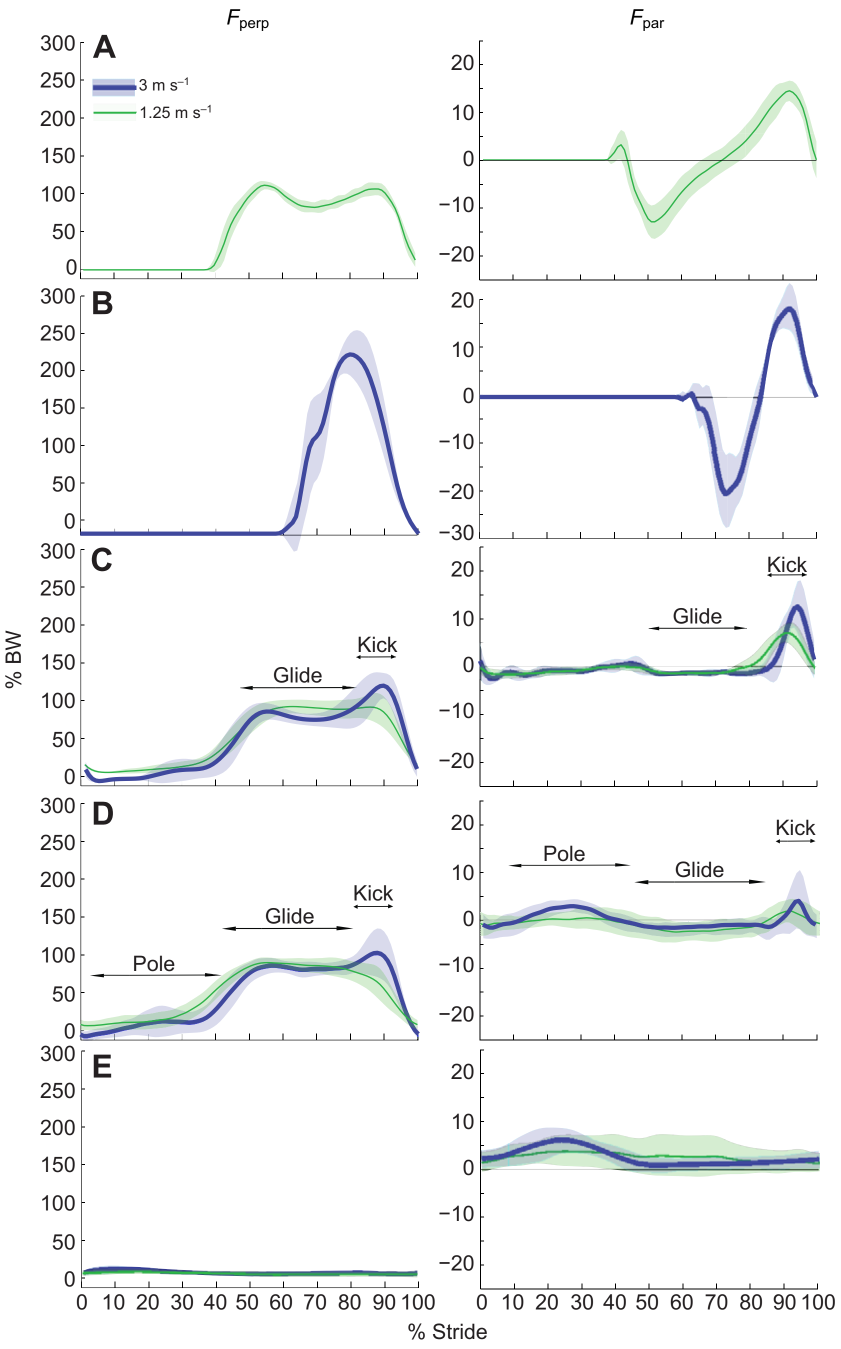

Fig. 1. Perpendicular and parallel forces averaged for all subjects (*N*=9). F_{perp}, perpendicular forces; F_{par}, parallel forces. (A) Walking, forces from the right foot only, at 1.25 m s^{-1}. (B) Running forces from the right foot only, at 3 m s^{-1}. (C) DIA NP, forces from the right roller ski only at both speeds. (D) DIA, forces from the right ski and right pole at both speeds. (E) Poling forces during DIA, right pole at both speeds. Forces are normalized to body weight (BW) and % stride begins and ends with toe-off or pole plant. Shaded areas represent ±s.d.

In Fig. 3, we highlight the KE of DIA NP at 3 m s^{-1}. KE initially increased throughout the kick, as the COM of the subject accelerated forward, and then the KE steadily decreased throughout the glide phase. We calculated the average rate of decrease in KE by finding the slope of the line (ΔKE/Δtime) during the glide phase. The average glide phase was 34.5% of the total stride, and the average stride time was 1.20 s. Therefore, there were 0.41 s during which the KE decreased by an average of 0.32 J kg^{-1}. The overall calculated rate of decrease in KE during the glide was thus 0.78 W kg^{-1}.

DISCUSSION

Although we used a different methodology, the general shapes of the roller skiing ground reaction forces were quite comparable to traces previously reported for on-snow skiing (Komi, 1987; Vähäsöyrinki et al., 2008), force instrumented roller skis (Bellizzi et al., 1998; Ohtonen et al., 2013) and force instrumented poles (Lindinger et al., 2009; Pellegrini et al., 2011; Stöggl and Holmberg, 2011). Also, the forces we recorded for walking and running were consistent with previously reported values (Nilsson and Thorstensson, 1989).

As expected, we found that walking has out-of-phase energy fluctuations. As the KE increases, the GPE decreases and vice versa. Because these two mechanical energies exchange through the inverted pendulum mechanism, the TE fluctuates by a lesser magnitude. We compared walking with DIA NP at 1.25 m s^{-1}, which is a normal walking speed. When the COM fluctuations of walking and DIA NP are side-by-side (Fig. 2), it is clear that DIA NP is mechanically very different from walking. The KE and GPE of the COM are out of phase in walking, and these same mechanical energies in DIA NP skiing are in phase, with the KE and GPE

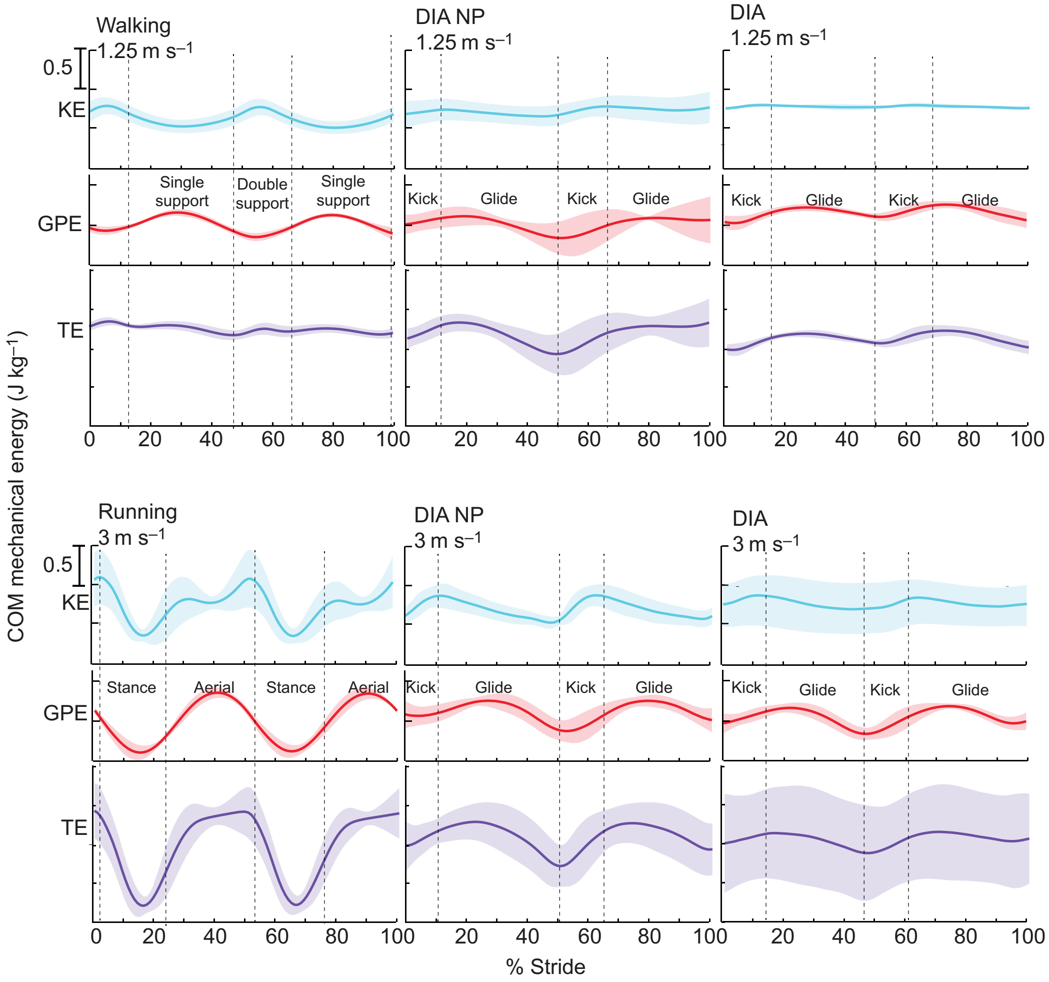

Fig. 2. Mechanical energy fluctuations of the COM for walking, running, DIA NP and DIA at 1.25 m s^{-1} and 3 m s^{-1}. KE, GPE and TE are normalized to bodyweight (J kg^{-1}), and a stride begins and ends with subsequent ipsilateral heel strikes or roller ski plant. Dotted vertical lines signify the beginning and end of different phases of each stride, defined on the plots between the lines. Plots represent the mean for *N*=9 ± s.d. (shaded areas).

fluctuating together, not oppositely. Moreover, compared with walking, the TE of DIA NP has a significantly larger magnitude of fluctuation. Thus, our results concur with previous findings (Pellegrini, 2011) regarding walking versus DIA. Also, during walking, the COM reaches its highest point during single leg stance. However, the COM during DIA NP and DIA was actually lowest during the middle of the stance phase at 1.25 m s^{-1}, so slow DIA is clearly not biomechanically similar to walking on this additional count.

As hypothesized, the fluctuations of the mechanical energies of DIA NP and DIA at 3 m s^{-1} are statistically indistinguishable from running, which has in-phase fluctuations of KE and GPE. The minimum KE and maximum GPE during a step in running have a phase difference of 173 deg, making the overall fluctuation pattern in phase. DIA NP also has in-phase fluctuations of KE and GPE, because the phase difference between the minimum KE and maximum GPE is ~177 deg for both 1.25 and 3 m s^{-1} roller skiing (Figs 2, 3). Also, at mid-stance, the COM is at its lowest point during both running and DIA at 3 m s^{-1}. Owing to these observations, we agree with previous statements that indeed, running and DIA have some biomechanical similarities (Minetti et al., 2000; Pellegrini, 2011).

Table 1. Magnitudes of mechanical energy fluctuations of the COM presented in Fig. 2 (means ± s.e.m., *N*=9)

Energy (J kg^{-1})	Walking 1.25 m s^{-1}	DIA NP 1.25 m s^{-1}	DIA 1.25 m s^{-1}
ΔKE	0.30±0.03	0.19±0.02*,‡	0.08±0.01*,‡
ΔGPE	0.34±0.02	0.54±0.11‡	0.27±0.04‡
ΔTE	0.21±0.03	0.74±0.13*,‡	0.30±0.05‡
	Run 3 m s^{-1}	DIA NP 3 m s^{-1}	DIA 3 m s^{-1}
ΔKE	0.97±0.12	0.41±0.05*	0.37±0.12*
ΔGPE	0.78±0.06	0.53±0.05*	0.45±0.09*
ΔTE	1.48±0.1	0.73±0.07*	0.55±0.16*

Statistical comparisons were run between the three modes of locomotion at each speed (1.25 and 3 m s^{-1}).
*Significantly different from walking or running at the same speed; ‡significantly different between DIA and DIA NP.

According to the spring–mass model for running, the stance leg acts as a spring, which can store and return energy with each step. In running, theoretically all the KE and GPE could be stored elastically and then recovered (Cavagna, 1977). Running relies on this elastic energy storage and return in the tendons and muscles of the stance leg to be mechanically and metabolically economical. During a DIA stride, the COM is briefly lowered (GPE decreases) during the initiation of the kick (i.e. preload). Slightly later during the kick, both KE and GPE increase together, which may reflect a recovery of GPE from elastic energy stored in the tendons. Through kinematic analysis, it has been previously concluded that elastic energy storage of GPE is possible due to the pre-stretch of the preload phase of DIA (Komi and Norman, 1987).

Owing to the rear-wheel ratchet mechanism, the preload phase in DIA is not a necessary movement for progression in roller skiing. Because expert skiers train so extensively on snow, the preload

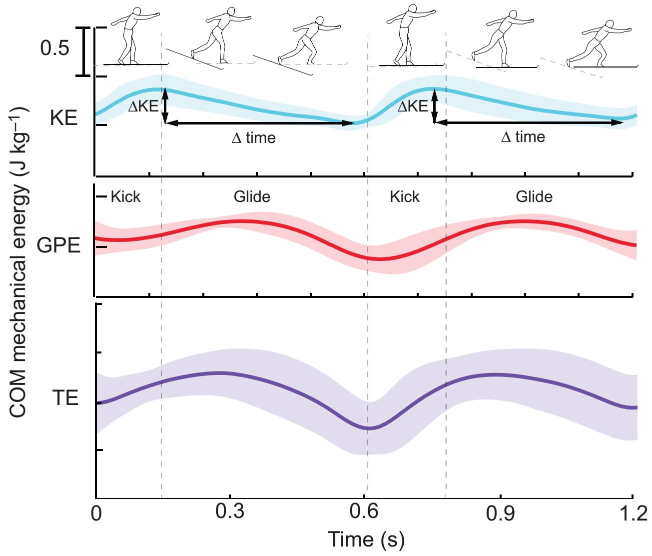

Fig. 3. Mechanical energy fluctuations of DIA NP. Each curve is the average of all subjects (N=9) ± s.d. (shaded area). KE, GPE and TE are measured in J kg^{-1}. Black arrows indicate how the change in the rate of kinetic energy (ΔKE/Δtime) decrease during the glide phase was calculated.

movement apparently carries over during dry-land training. During on-snow DIA, the preload is used to set the wax pocket and grip the snow beneath the ski. Although there may be some elastic energy storage during this preload phase, another likely purpose of the preload stretch shortening is to enhance force production from the muscles.

However, running is an economical mode of locomotion primarily because it can also store KE as elastic energy, not just GPE. For each step in DIA, muscular energy is required to kick and propel the skier into the glide phase. But in DIA skiing, the KE decreases throughout the glide phase, as the energy previously put in to the system is lost (Fig. 3). The overall calculated rate of decrease in KE during the glide was thus 0.78 W kg^{-1}. Where does this 0.78 W kg^{-1} go? Was it stored elastically or dissipated as frictional heat? To address that question, we estimated the energy lost due to the rolling resistance of the roller skis on the treadmill. The calculated mean force required to tow a subject on the roller skis, i.e. the rolling resistance, was 16.2 N (Fig. 4). Because power equals the product of force and velocity, at 3 m s^{-1}, this results in a power dissipation of 48.6 W. Normalized to body mass, these calculations suggest that 0.70 W kg^{-1} was dissipated as friction during the glide phase. During the glide phase of DIA, almost all of the KE generated for each step is dissipated (as rolling friction) and therefore cannot be stored and returned. We calculated that on average 89.7% of the energy input is lost due to rolling resistance and therefore cannot be stored within the stance leg as elastic energy. We conclude that running and DIA are fundamentally different with regards to mechanical energy fluctuations and DIA mechanics should not be likened to a spring–mass model.

A further interesting result of this study, and a possible area of future study, was the effect of using poles. When the poles are used for DIA, the KE fluctuations become smoother and, as a result, so do the TE fluctuations. During DIA, the smoother fluctuations of the KE are still almost exactly in phase, as in running, but the overall loss of KE during the glide phase is less. It seems that a function of the poles is to maintain a more constant forward velocity, by reducing the slowing down during each glide phase. This raises the question of pole optimization. Does skillful use of poles produce a more mechanically and metabolically economical skiing technique?

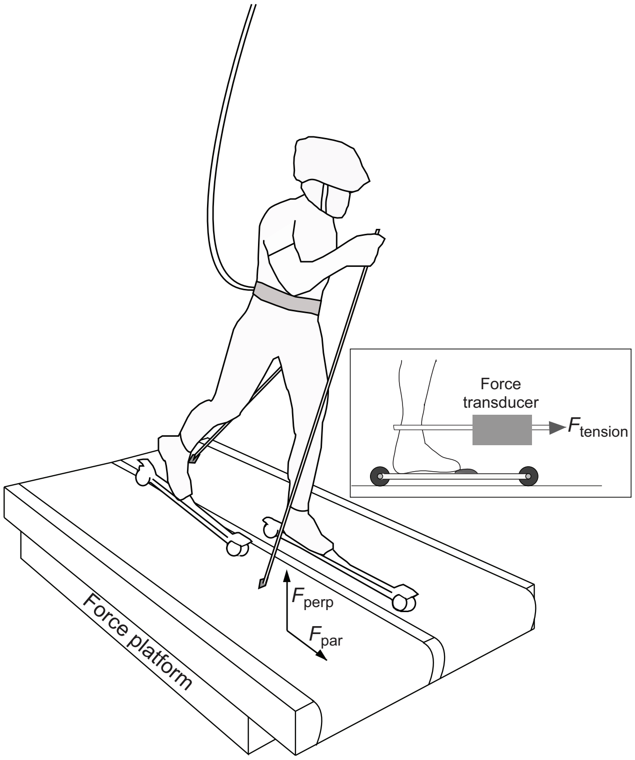

Fig. 4. Experimental setup. A subject roller skiing on our custom-built, dual-belt force instrumented treadmill. Device records parallel force (F_{par}) and perpendicular force (F_{perp}) from under the right side of the belt. Inset: method for recording the rolling resistance of the roller skis (inset modified from Pellegrini, 2011).

Our findings are specific to roller skiing but can probably be generalized to on-snow skiing. Roller skis are used widely for dry-land training, as well as for biomechanical research. Approximately 72% of cross-country skiing scientific papers published since 2005 utilized roller skis on treadmills as a proxy for on-snow cross-country skiing (Pellegrini, 2011). This is because on-snow cross-country ski studies can be challenging due to environmental factors and variable snow conditions. The utilization of a ski treadmill in conjunction with force measurement can provide better experimental control than is possible in field studies (Smith, 1990).

In conclusion, we found that DIA clearly differs biomechanically from walking and running. The KE and GPE mechanical energy fluctuations of both DIA NP and DIA initially appear similar to running, but, unlike running, most of the KE in DIA is lost to rolling resistance of the roller skis and not stored elastically. There is a possibility of some GPE being stored elastically during the preload phase of DIA. Overall, we reject our hypothesis because DIA biomechanics are unique and fundamentally different from both walking and running.

MATERIALS AND METHODS

Although it is possible to estimate mechanical energy fluctuations of the COM using kinematic analysis and estimates of body segment mass and inertia values, we chose to directly integrate the ground reaction force signals (Cavagna, 1975). Many studies have characterized the kinematics of DIA (Smith, 1992), and a few groups have quantified the forces exerted at the skis and/or poles during DIA (Bellizzi et al., 1998; Komi, 1987;

Lindinger et al., 2009; Ohtonen et al., 2013; Pellegrini, 2011; Stöggl and Holmberg, 2011; Vähäsöyrinki et al., 2008). However, to our knowledge, none have integrated the forces to calculate the COM energy fluctuations.

Experimental protocol

We collected data for nine subjects, four female, five male, [age, 26.3±3.3 years; mass, 69±9 kg; height, 175±8 cm (mean ± s.d.)]. Subjects had an average of six years experience with cross-country skiing in the classic style, ranging in skill from citizens racers to World Cup racers, and all had at least moderate experience on roller skis. All of these healthy subjects gave written, informed consent according to the University of Colorado Institutional Review Board approved protocol.

Subjects walked (1.25 $\mathrm{m\,s^{-1}}$), ran (3.0 $\mathrm{m\,s^{-1}}$) and roller skied (1.25 and 3.0 $\mathrm{m\,s^{-1}}$) using the diagonal stride technique on a custom-built, dual-belt treadmill (Kram et al., 1998; Franz and Kram, 2014) with a force platform mounted underneath the right treadmill. The treadmill consisted of two belts side-by-side measuring 51 cm each in width with a useful top surface length of 191 cm. All subjects used PRO-SKI C2 Classic roller skis (Sterners, Dala-Järna, Sweden), their own ski boots, and poles. Roller skis are commonly use for dry-land training and are composed of two rubber wheels, one in front and one behind the boot. The back wheel has a ratcheting mechanism which allows for uni-directional travel anteriorly and simulates on-snow grip. In most trials, the subjects used a pole in each hand. We replaced their metal pole tips with rubber tips (Holmberg et al., 2005). For safety during the roller ski trials, each subject wore a bicycle helmet and a waist belt that we secured to the ceiling with a slack rope (Fig. 4). For the walking and running trials, they used their own running shoes and no poles.

To begin, participants warmed-up by roller skiing for at least 15 min to become comfortable on the treadmill. Further, this ensured that the roller ski wheels and bearings reached a proper temperature (Ainegren et al., 2008). Subjects then walked and skied at 1.25 $\mathrm{m\,s^{-1}}$ and then ran and skied at 3 $\mathrm{m\,s^{-1}}$. All skiing trials utilized the diagonal stride technique (Smith, 1992). Each trial of walking, running or skiing lasted 2 minutes with 2 minutes of rest in between.

Roller skiing trials were performed using four different measurement configurations: (1) with one ski and one pole on each belt (split), recording forces from under the right ski and right pole. (2) With the right pole only on the right belt and both skis and the left pole on the left belt, recording forces from only the right pole. (3) With both skis and both poles on the right belt, recording the forces from the entire body and all equipment. (4) With one ski on each belt, but no poles (DIA NP), recording the forces from the right ski only. These four measurement configurations allowed us to directly quantify pole forces, ski forces and the fluctuations of the mechanical energy of the COM. We recorded walking forces with one foot on each belt and with both feet on the right and running forces with both feet on the right belt.

During each trial, we recorded both F_{perp} and F_{par} (anterior–posterior) forces for 15 s at 1000 Hz (LabView 8.0, National Instruments, Austin, TX, USA). After data collection, we filtered the walking and running ground reaction force (GRF) data using a recursive fourth-order Butterworth low-pass filter with a cut-off frequency of 25 Hz. Owing to the lower stride frequency of roller skiing, we processed the roller skiing GRF data with a cut-off frequency of 15 Hz. We wrote a custom MATLAB (Natick, MA, USA) script to identify events for all three modes of locomotion.

In walking and running, we define a stride as beginning and ending with subsequent right foot heel strikes. In DIA, a stride is from right pole plant to right pole plant. In DIA NP, a stride begins and ends right after the right roller ski kick, so the different stride phases are aligned to DIA. We wrote a MATLAB program that detected an average of 15 strides for each subject, and we calculated the average parallel and perpendicular peak forces for all subjects.

Mechanical energy fluctuations

From the force recordings during DIA NP and DIA, we calculated the KE and GPE of the COM (Cavagna, 1975). The DIA NP trials simplified the comparisons between walking, running and roller skiing. We custom wrote a MATLAB integration program modified for DIA NP and DIA. Because we only recorded forces from under the right belt, we created a composite force file that assumed symmetry and simulated combined left and right forces (Franz and Kram, 2013). From these force files, we used the technique developed by Cavagna (Cavagna, 1975) and modified by Snyder (Snyder et al., 2012) to integrate the forces to yield COM vertical displacement and the resultant COM velocity.

In order to calculate the GPE, we used F_{perp}, the force perpendicular to the treadmill belt. We calculated the perpendicular acceleration (a_{perp}) equal to (F_{perp}–$m\boldsymbol{g}$)/m, where m is the participant's body mass and $\boldsymbol{g}$ is gravitational acceleration, 9.81 $\mathrm{m\,s^{-2}}$. We calculated the perpendicular velocity (v_{perp}) of the COM by integrating a_{perp} with respect to time and adding an integration constant of the speed of the treadmill. We calculated COM vertical displacement (Δh) by integrating v_{perp} with respect to time and adding an integration constant, which assumes the average vertical velocity is equal to zero. The instantaneous GPE was calculated as $m\boldsymbol{g}\Delta h$.

To calculate the instantaneous KE fluctuations of the COM, we first determined the instantaneous acceleration in each direction (a_{perp} and a_{par}) equal to (F_{perp}–$m\boldsymbol{g}$)/m and F_{par}/m, respectively. Next, we calculated the instantaneous velocities (v_{perp} and v_{par}) by integrating the acceleration (a_{perp} and a_{par}) with respect to time. We added an integration constant equal to the velocity of the treadmill to find a_{par} and for a_{perp} we assumed that the COM returns to the same height at the beginning of each stride. Finally, we combined these perpendicular and parallel velocities (v_{perp} and v_{par}) using the Pythagorean Theorem to determine the resulting instantaneous velocity (v_{result}) of the COM and KE, $0.5\,mv^2_{\mathrm{result}}$.

We calculated the phase difference (α) of the fluctuations of KE and GPE by adapting a previous method utilized for walking phase difference calculations (Cavagna et al., 1983). We calculated the phase difference (α), which is equal to 360 deg multiplied by the ratio of $\Delta t/T$. Δt is the difference between the time at which KE was minimum and GPE was maximum, and T is the step period (i.e. the period of repeating changes in forward and vertical velocity of the COM). As defined here, each stride consisted of two step periods. Given this definition of α, if KE and GPE fluctuated perfectly in phase, α would be equal to 180 deg, and if the fluctuations were perfectly out of phase, α would equal 0 deg. If the minimum KE occurs after the maximum GPE during each step, then $\alpha>0$ deg, and $\alpha<0$ deg if the minimum KE occurs before.

In order to indirectly evaluate the possibility of storage and return of elastic energy, it was important to estimate the power dissipated as friction from the roller skis. To do so, we measured the rolling friction of the roller skis by a towing test described previously (Sandbakk et al., 2010). A force transducer measured the force (Alpine Digital Scale, Feedback Sports, Golden, CO, USA) and we averaged over six trials. We found the force required to tow a subject on the level force treadmill at 3 $\mathrm{m\,s^{-1}}$ (Fig. 4). The mean coefficient of rolling resistance was $C_{\mathrm{rr}}=0.027$. We used the mean force required to tow a subject on roller skis to calculate the power required to tow the subject against the rolling resistance (power=force×velocity). The relative power dissipated to rolling resistance is the product of the towing force and the treadmill velocity divided the mass of the subject, roller skis and poles. This allowed us to track the fate of the decreases in KE and GPE. If KE and GPE are effectively stored as elastic energy, then there will be little evidence of power dissipation to friction.

Statistics

We used MATLAB to perform repeated-measures ANOVA with a Tukey's *post hoc* analysis to find significant changes in peak forces, differences in magnitudes of fluctuation of the COM, and differences in α between speeds and modes of locomotion. Our criterion for significance was $P<0.05$.

Competing interests

The authors declare no competing financial interests.

Author contributions

A.K. organized and performed all data collection and data processing and wrote the first draft of the manuscript. E.H. aided in data collection, subject recruitment and overall study design. R.K. and H.C.H. contributed to the conception and design of the study, the analyses and the writing of the manuscript.

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References

Ainegren, M., Carlsson, P. and Tinnsten, M. (2008). Roller ski rolling resistance and its effects on elite athletes' performance (P225). *Engineering of Sport* **7**, 393-400.

Alexander, R. M. (2003). *Principles of Animal Locomotion*. Princeton, NJ: Princeton University Press.

Bellizzi, M. J., King, K. A., Cushman, S. K. and Weyand, P. G. (1998). Does the application of ground force set the energetic cost of cross-country skiing? *J. Appl. Physiol.* **85**, 1736-1743.

Cavagna, G. A. (1975). Force platforms as ergometers. *J. Appl. Physiol.* **39**, 174-179.

Cavagna, G. A. (1977). Storage and utilization of elastic energy in skeletal muscle. *Exerc. Sport Sci. Rev.* **5**, 89-129.

Cavagna, G. A. and Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. *J. Physiol.* **268**, 467-481.

Cavagna, G. A., Heglund, N. C. and Taylor, C. R. (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am. J. Physiol.* **233**, R243-R261.

Cavagna, G. A., Franzetti, P. and Fuchimoto, T. (1983). The mechanics of walking in children. *J. Physiol.* **343**, 323-339.

Chang, Y.-H. and Kram, R. (2007). Limitations to maximum running speed on flat curves. *J. Exp. Biol.* **210**, 971-982.

Farley, C. T. and Ferris, D. P. (1998). Biomechanics of walking and running: center of mass movements to muscle action. *Exerc. Sport Sci. Rev.* **26**, 253-285.

Franz, J. R. and Kram, R. (2013). Advanced age affects the individual leg mechanics of level, uphill, and downhill walking. *J. Biomech.* **46**, 535-540.

Franz, J. R. and Kram, R. (2014). Advanced age and the mechanics of uphill walking: a joint-level, inverse dynamic analysis. *Gait Posture* **39**, 135-140.

Holmberg, H. C., Lindinger, S., Stöggl, T., Eitzlmair, E. and Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Med. Sci. Sports Exerc.* **37**, 807-818.

Hu, D. L., Chan, B. and Bush, J. W. (2003). The hydrodynamics of water strider locomotion. *Nature* **424**, 663-666.

Ker, R. F., Bennet, M. B., Bibby, S. R., Kester, R. C. and Alexander, R. McN. (1987). The spring in the arch of the foot. *Nature* **325**, 147-149.

Komi, P. V. (1987). Force measurements during cross-country skiing. *J. Appl. Biomech.* **3**, 370-381.

Komi, P. V. and Norman, R. W. (1987). Preloading of the thrust phase in cross-country skiing. *Int. J. Sports Med.* **8 Suppl. 1**, S48-S54.

Kram, R., Griffin, T. M., Donelan, J. M. and Chang, Y. H. (1998). Force treadmill for measuring vertical and horizontal ground reaction forces. *J. Appl. Physiol.* **85**, 764-769.

Lindinger, S. J., Gopfert, C., Stöggl, T., Müller, E. and Holmberg, H. C. (2009). Biomechanical pole and leg characteristics during uphill diagonal roller skiing. *Sports Biomech.* **8**, 318-333.

Marsh, R. L., Olson, J. M. and Guzik, S. K. (1992). Mechanical performance of scallop adductor muscle during swimming. *Nature* **357**, 411-413.

McMahon, T. A., Valiant, G. and Frederick, E. C. (1987). Groucho running. *J. Appl. Physiol.* **62**, 2326-2337.

Minetti, A. E. (2004). Passive tools for enhancing muscle-driven motion and locomotion. *J. Exp. Biol.* **207**, 1265-1272.

Minetti, A. E., Cotelli, F., Canclini, A., Susta, D., Saibene, F. and Smith, G. A. (2000). Individual economy and general mechanics in cross-country skiing. In *Science and Skiing II* (ed. E. Müller, H. Schwameder, C. Raschner, S. Lindinger and E. Kornexl), pp. 30-42. Hamburg: Verlag Dr. Kovac.

Nilsson, J. and Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiol. Scand.* **136**, 217-227.

O'Dor, R. K. (2013). How squid swim and fly. *Can. J. Zool.* **91**, 413-419.

Ohtonen, O., Lindinger, S., Lemmettylä, T., Seppälä, S. and Linnamo, V. (2013). Validation of portable 2D force binding systems for cross-country skiing. *Sports Eng.* **16**, 281-296.

Pellegrini, B. (2011). *Biomechanical and Physiological Characterization of Cross-Country Skiing Techniques. Analysis of the Selection Between Techniques.* PhD dissertation, University of Verona, Italy.

Pellegrini, B., Bortolan, L. and Schena, F. (2011). Poling force analysis in diagonal stride at different grades in cross country skiers. *Scand. J. Med. Sci. Sports* **21**, 589-597.

Rubenson, J., Heliams, D. B., Lloyd, D. G. and Fournier, P. A. (2004). Gait selection in the ostrich: mechanical and metabolic characteristics of walking and running with and without an aerial phase. *Proc. Biol. Sci.* **271**, 1091-1099.

Sandbakk, Ø., Holmberg, H. C., Leirdal, S. and Ettema, G. (2010). Metabolic rate and gross efficiency at high work rates in world class and national level sprint skiers. *Eur. J. Appl. Physiol.* **109**, 473-481.

Smith, G. A. (1990). Biomechanics of crosscountry skiing. *Sports Med.* **9**, 273-285.

Smith, G. A. (1992). Biomechanical analysis of cross-country skiing techniques. *Med. Sci. Sports Exerc.* **24**, 1015-1022.

Snyder, K. L., Kram, R. and Gottschall, J. S. (2012). The role of elastic energy storage and recovery in downhill and uphill running. *J. Exp. Biol.* **215**, 2283-2287.

Stöggl, T. and Holmberg, H. C. (2011). Force interaction and 3D pole movement in double poling. *Scand. J. Med. Sci. Sports* **21**, e393-e404.

Tobalske, B. W., Peacock, W. L. and Dial, K. P. (1999). Kinematics of flap-bounding flight in the zebra finch over a wide range of speeds. *J. Exp. Biol.* **202**, 1725-1739.

Vähäsöyrinki, P., Komi, P. V., Seppälä, S., Ishikawa, M., Kolehmainen, V., Salmi, J. A. and Linnamo, V. (2008). Effect of skiing speed on ski and pole forces in cross-country skiing. *Med. Sci. Sports Exerc.* **40**, 1111-1116.

Wilson, R. (1991). To slide of to stride: when should Adelie penguins (Pygoscelis adelie) toboggan. *Can. J. Zool.* **69**, 221-225.