WALKING, RUNNING, AND GLIDING:
THE BIOMECHANICS AND ENERGETICS OF DIAGONAL STRIDE SKIING

by

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Walking, Running and Gliding: The Biomechanics and Energetic of Diagonal Stride Skiing

Thesis directed by Rodger Kram, Ph.D.

Diagonal stride is the classic style of cross-country skiing involving alternating arm and leg movements that appear similar to both walking and running, but is it truly biomechanically and energetically similar to walking and running? To better understand the fundamental biomechanics of diagonal stride skiing, we compared its ground reaction forces, mechanical energy fluctuations of the center of mass and metabolic energy consumption to walking and running. We hypothesized that diagonal stride skiing would be biomechanically more similar to running, but with a lesser energetic cost.

I recorded ground reaction forces of nine subjects roller skiing on a force-measuring treadmill, a method that catalyzed the study of walking and running but had never been utilized in cross-country skiing studies. I analyzed the changes in the perpendicular and parallel forces with increasing speed (1.25 and 3 m/s) and incline (Level, 3°, and 6°). Force recordings were similar to those previously recorded with other devices, thus validating our method.

From the forces, we calculated the mechanical energy fluctuations of the center of mass of level walking, running, and diagonal stride skiing (with and without poles). Diagonal stride skiing had almost in-phase fluctuations of kinetic and gravitational potential energies, similar to running. In-phase fluctuations of the center of mass allow runners to store and recover elastic energy, so that less mechanical energy input is required with each step. However, in diagonal stride skiing, almost all of the kinetic energy losses were due to the rolling resistance of the skis and could not be stored elastically.

I also compared the energy expenditure of each locomotion form using open-circuit expired gas analysis. Diagonal skiing had a metabolic rate greater than walking and lower than running at the same speeds. Also, I found no significant metabolic advantage of using

poles during level roller skiing. Overall, by successfully using a force-measuring treadmill, I found that diagonal skiing is a unique form of locomotion that does not utilize elastic energy storage like running, but has a lower energetic cost.

Acknowledgements

The past two years of my graduate school career can be summed up in one word, "luck". I was lucky to meet Rodger Kram and somehow fall into his good graces and I was equally as lucky to meet Hans-Christer Holmberg and fall into the world of skiing research. I never imagined that I would become the intermediate between two great minds, and I hope that somehow I have lived up to both of their ideals.

I am very grateful to Rodger for his outstanding mentorship and infectious enthusiasm for research. As the best teacher I have ever had, he taught me countless lessons about life and learning, in addition to how use a drill and a socket wrench. I would also like to thank HC for his insight, support and friendship as well as introducing me to the skiing research community. I am extremely grateful to Eliska Hajkova for being the best research assistant and cross-country skier there is, she was vital to every aspect of this project. I would also like to thank the members of the Locomotion and Neuromechanics laboratories for their support, friendship, and most of all, Matlab help.

Major thanks are in order for the other members of my thesis committee, Alena Grabowski and Bill Byrnes, who graciously donated their time and energy into reviewing this thesis.

Finally, I thank my boyfriend, Mike, for supporting me and dropping everything to save my future in research with his soldering expertise.

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Introduction

The main objective of my thesis research was to apply the proven methodologies used for walking and running studies to cross-country skiing. The thesis is split into three chapters all based upon one group of subjects who underwent a very lengthy experiment. Each chapter is intended to one day become a publication. The first chapter is focused on the dual-belt force measuring treadmill. This is a tool that has proven itself time and time again to be a fundamental part of locomotion research. I sought to validate this system as a possibility for force measurements in different cross-country skiing techniques. The technique analyzed in this paper is diagonal stride, which has many similarities to both walking and running. In chapter Two, using the force data from the first study, I calculated and compared the mechanical energy fluctuations of the center of mass of diagonal stride skiing, walking and running to see if they truly have biomechanical similarities. In the last section, chapter Three, I also compared walking, running, and diagonal stride skiing, but this time energetically. I analyzed the metabolic rates of all three modes of locomotion at similar speeds to see which has the lowest energetic cost. In this study, I also looked at the effects of the poles in diagonal stride skiing and how the energetic cost changes when skiing without them. Together these studies have hopefully introduced a useful new methodology to the cross-country skiing research and expanded our understanding of ski-enhanced locomotion.

CHAPTER I

XC Skiing on a Force Measuring Treadmill

1.1 Introduction

Diagonal stride skiing (DIA) is a classic technique of cross-country skiing, which resembles walking while poling alternately with each arm and kicking the opposite leg. For decades, many kinematic aspects of the stride and movement of DIA have been studied (Smith, 1992), but the underlying forces of DIA have only been analyzed a few times. This is most likely because DIA is a form of locomotion that is performed under special conditions, with special testing requirements, and cold, humid weather can be very demanding on equipment and researchers alike (Komi, 1987).

The ground reaction forces (GRF) of DIA have been studied using two main approaches. One group ingeniously used force plates beneath a snowy ski track and characterized both perpendicular (F_{perp}) and parallel (F_{par}) forces across varying speeds (Komi, 1987; Vahasoyrinki et al., 2008). A few other groups have quantified the forces using strain gauges within roller skis (Bellizzi et al., 1998; Hoset et al., 2013; Ohtonen et al., 2013). Pole forces in DIA have been more commonly studied, as they are in some ways technically easier to obtain. Many have used force measuring devices within the pole itself along with motion capture technology to quantify the F_{perp} and F_{par} GRFs from the pole during a cross-country skiing stride (Bellizzi et al., 1998; Lindinger et al., 2009; Pellegrini et al., 2011; Stöggl and Holmberg, 2011). However, to our knowledge, no one has utilized a force measuring treadmill (FTM), a technology that catalyzed the study of walking and running biomechanics, to measure the GRFs of cross-country skiing.

Walking and running have well characterized mechanics, but it was not until the invention of the force measuring treadmill (FTM) that locomotion studies sped up significantly. Utilization of the FTM substantially reduced data-collection time for locomotion research because the forces were validated to be identical to over ground experiments. FTM's also allow instant feedback to subjects, and support experiments that were previously impossible (Kram et al., 1998). Since their invention, FTMs have been widely used for walking and running research, so it is curious why other locomotion research has not also exploited this valuable tool.

To fully understand DIA biomechanics, it is important to measure and analyze the GRFs of the ski and poles separately and together. Both the kick of the ski and pole push contribute to a skier's forward progression, but their independent functional significance "may be more complex than that of the ground reaction forces in running and walking" (Komi, 1987). We used the same methods as in walking and running research, and quantified the skiing GRFs using a FTM. We were able to record independent forces of the pole and ski at multiple inclines and speeds while avoiding the challenges of outdoor testing.

The purpose of this experiment was to validate a FTM as an effective tool for future cross-country ski research and to further analyze the ground reaction forces during diagonal stride skiing. We asked two questions:

1. How do ground reaction forces measured by the force-instrumented treadmill compare to previous findings?
2. How do the perpendicular and parallel ground reaction forces change with speed and incline in diagonal stride roller skiing?

We hypothesized that our perpendicular and parallel force measurements would be similar to previous instrumented roller ski studies and that both perpendicular and parallel forces would increase at faster speeds and up steeper inclines.

1.2 Methods

Experimental Protocol

We collected data for 9 subjects, 4 female, 5 male, (age: 26.3 ± 3.3 years, mass: 69 ± 9 kg, height: 175 ± 8 cm (mean±SD)). Subjects had an average of six years experience with cross-country skiing in the classic style, ranging in skill from recreational 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 IRB approved protocol.

Subjects roller skied in DIA on a custom-built force instrumented dual-belt treadmill (Franz and Kram, 2014) with a force platform mounted underneath the right belt. All subjects used PRO-SKI C2 Classic roller skis (Sterners, Dala-Järna, Sweden), their own ski boots and their own poles. We replaced their pole tips with rubber tips (Holmberg et al., 2005). For safety, each subject wore a bicycle helmet and a waist belt that we secured to the ceiling with a slack rope (Fig. 1.1).

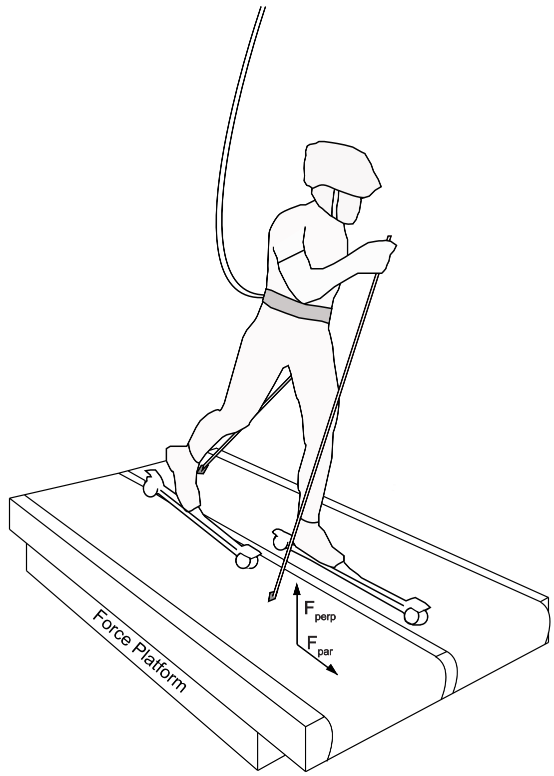

Figure 1.1. Experimental setup. Subject roller skiing on our custom-built, dual belt force instrumented treadmill. Device records perpendicular force (F_{perp}) and parallel force (F_{par}) from under the right side belt.

The subjects completed three data collection sessions on separate days during which they roller skied at either level, 3, and 6 degree inclines. The separation in sessions allowed time for us to change the slope of the treadmill, which involved removing the treadmill from the force platform and installing the appropriate aluminum wedges. Because we had to accommodate the subject's schedules, we were unable to truly randomize the order of the sessions for each subject. However, because there were at least two days between each session, fatigue was not an issue and it is hard to imagine that one session systematically affected the subsequent sessions.

To begin, participants warmed-up by roller skiing for at least 15 minutes to become comfortable on the treadmill. Further, this assured that the roller ski wheels and bearings reached a proper temperature. Subjects then skied at 1.25m/s and 3m/s. All skiing trials utilized DIA (Smith, 1992). Each trial lasted two minutes with two minutes of rest in between. Roller skiing trials were performed using two different configurations: 1. with one ski and one pole on each belt (split), and 2. with only the right pole on the right belt and both skis and the left pole on the left belt. These two configurations allowed us to quantify pole and ski forces together and separately.

During each trial, we recorded both perpendicular (F_{perp}) and parallel (F_{par}) forces for 15 seconds at 1,000 Hz (LabView 8.0, National Instruments, Austin, TX, USA). After data collection, we processed the roller skiing ground reaction force (GRF) data with a recursive fourth-order Butterworth low-pass filter with a cutoff frequency of 15 Hz. We wrote a custom Matlab (Natick, MA USA) script to identify events for DIA.

We defined a DIA stride as beginning and ending with consecutive right pole plants. We wrote a Matlab program that detected an average of 15 strides for each subject and we calculated the average F_{perp} and F_{par} peak forces for all subjects.

Stats

We used SPSS to perform a repeated measures ANOVA to analyze changes in peak forces with increasing speed or incline with $p<0.05$ needed for significance.

1.3 Results

The vertical forces during DIA had five general phases throughout each stride as identified previously (Vahasoyrinki et al., 2008). The skiing stride was defined as starting with a 1) pole plant followed by a 2) glide phase of the ipsilateral roller ski. Next, there was a 3) pre-load phase when the F_{perp} decreased, as the center of mass was lowered, in preparation for the 4) kick, when the ipsilateral roller ski pushed off the treadmill 5) as the contralateral roller ski moved forward into the glide phase (Fig. 1.2).

As expected, the greatest F_{perp} was measured at the fastest speed (3 m/s) and the steepest incline (6 degrees) (Fig. 1.2). At 3 m/s and 6 degrees, the F_{perp} peak was 134%BW for the kick and the propulsive F_{par} peaks were 10.2%BW and 26.5%BW for the pole and kick respectively (Table 1.1). All measured peak forces were significantly greater due to speed, but only the F_{par} for both pole and kick were greater with an increased incline.

An accurate poling force was measured from configuration 2, only the right pole on the force-measuring belt. During configuration 1, GRFs are recorded from both the pole and roller ski simultaneously, and any overlap could add extra perpendicular force to the 'poling' section of the stride. The independently measured pole force had a lower F_{perp} than the pole force recorded using configuration 1. However the F_{par} from configuration 2 was not significantly different from the F_{par} measured in configuration 1 ($p=0.39$). As the roller ski begins the glide phase, the ratchet mechanism has not engaged, so there are only perpendicular GRFs and no parallel GRFs due to the roller ski during the poling phase.

When measured independently from roller ski forces at 3 m/s and a 6° incline, the F_{perp} of the pole was 15.1%BW (±0.61SEM) and the F_{par} was 11.58%BW (±1.46SEM). The pole F_{perp} at 3m/s at level had a peak of 10.0%BW (±1.03SEM) and the F_{par} peaked at 6.2%BW (±1.07SEM) (Fig. 1.3). Unfortunately, we were unable to resolve the small poling propulsive forces at 1.25 m/s.

We could only discern the preload phase in the individual force traces of highly skilled skiers and it was not apparent in averaged force traces of Figure 1.1. The F_{perp} and F_{par} of recreational skiers were also inconsistent when compared to an elite skier (Fig. 1.4).

Recreational skiers had less distinction between their glide and kick phases and also hit down on the treadmill rather than sliding smoothly into the glide phase. The collision of the ski with the belt caused the large F_{perp} spikes at the beginning of the glide phase of the recreational skiers. However, the poling forces were found to be similar between elite and recreational skiers.

1.4 Discussion

All F_{perp} and F_{par} traces were quickly and easily recorded at each incline and speed. The GRFs traces were similar in shape to previous force measurements recorded from instrumented roller skis. However, an important difference between our FTM recorded forces and those recorded over snow (Vahasoyrinki et al., 2008) was the absence of any discernable negative, or braking, forces in DIA. That absence was of course due to the roller skis themselves, which allowed the skiers to glide through the impact of the ski hitting the ground, rather than decelerating the body. Overall, the forces exerted during roller skiing can be reliably measured using a FTM . We accept our first hypothesis because our measured forces are very close in pattern and magnitude to forces recorded previously by instrumented bindings.

We also discovered that it is possible to record perpendicular and parallel pole forces independently and reliably using a FTM. By shifting the subject over so only their right pole was on the force-measuring belt, the F_{perp} and F_{par} of the pole was determined. These values are also consistent with previous research using instrumented poles.

We partially accept our second hypothesis. Peak F_{perp} increased at the faster speed but the change in incline did not have a significant effect. However, F_{par} peaks became greater at the faster speed and up the steeper inclines for both the pole and kick force. Because the arms supply force primarily for propulsion, the F_{par} of the poles increases immensely on an incline (Bellizzi et al., 1998). Therefore, we can conclude that when changing from a flat to an incline, a skier will apply more propulsive force of both their ski and pole.

The differences in force traces we noted between elite and recreational individuals suggest that a FTM could be a useful tool for training. As mentioned before, FTMs are useful not only for the ease of research, but also because they can give real-time feedback. While roller skiing on the treadmill, force traces could be shown to the skier so they can adjust their technique. This method could be useful for training a preload phase or greater consistency between strides.

Our experiment focused on the diagonal stride technique only, but a FTM could be utilized for research on other classic skiing forms and possibly for skating as well. We have successfully collected data for both double pole and double pole with a kick techniques of classic XC. As with DIA, it is possible to measure independent forces of the pole during double pole and double pole kick by simply shifting the subject over on the belts. However, we have not attempted skating on the FTM. We are unsure if it would be possible to record skating forces across two belts, because the roller skis would not be allowed to cross in the back. Also, the belts would need to be much wider to allow for the medio-lateral strides used in skating techniques.

Overall, the FTM is an extremely useful tool for cross-country research and should be utilized more in the future. However, for a FTM to be more effective, a few changes could be made. Implementing force measurements underneath both belts, rather than just the right belt, would save time and allow for simultaneous left and right measurements. Also, a ski treadmill needs to have longer and wider belts than a traditional running treadmill to allow for the longer length of roller skis and the width of the poles. We would have preferred a longer and wider treadmill to make the skiers feel more comfortable and safe. Also, a better ski force treadmill would have easier incline adjustment so many inclines could be analyzed in one session.

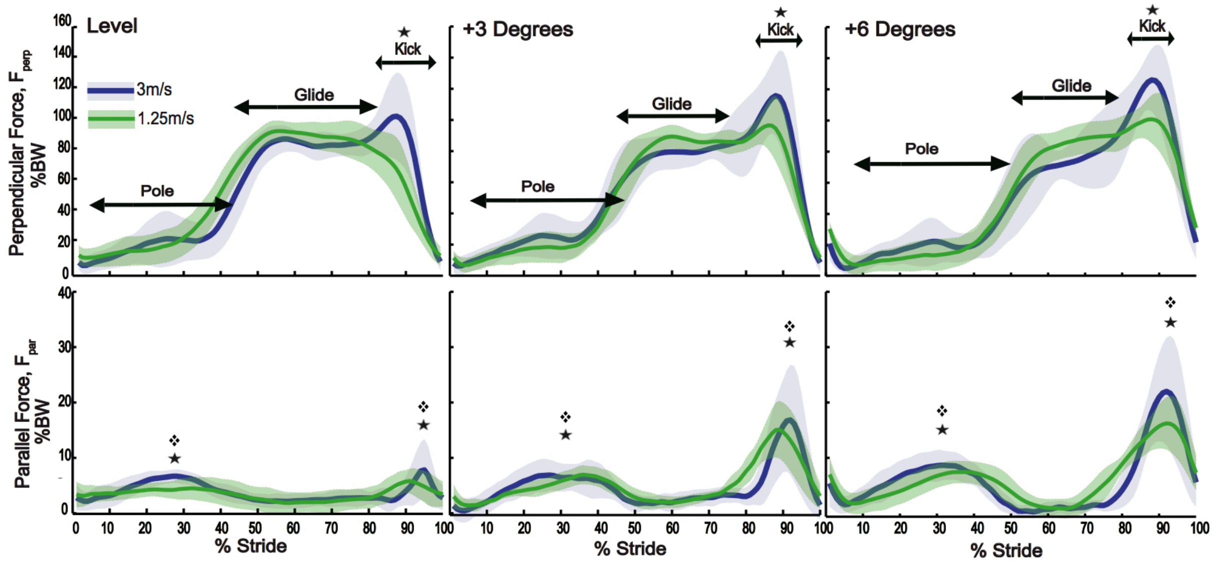

Figure 1.2. Perpendicular and parallel forces averaged from all subjects ± shaded standard deviation from diagonal stride skiing at 1.25 and 3 m/s. Forces are normalized to body weight (BW) and % stride begins and ends with pole plant. Diamonds (❖) represent a significant difference due to incline and stars (★) represent a significant difference due to speed. We defined significance as $p<.05$.

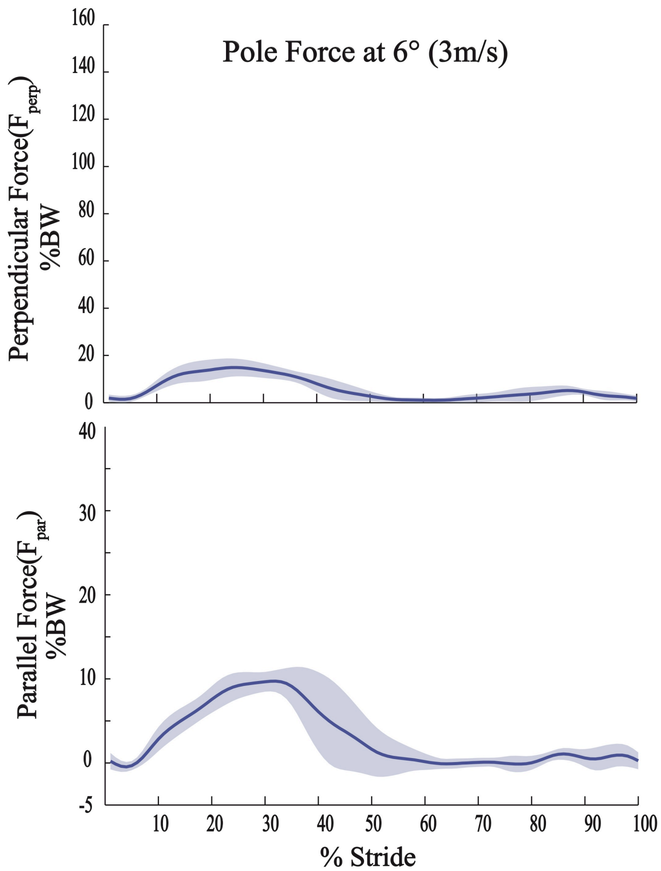

Figure 1.3. Average perpendicular and parallel poling forces ± shaded standard deviation at 3 m/s and 6 degree incline.

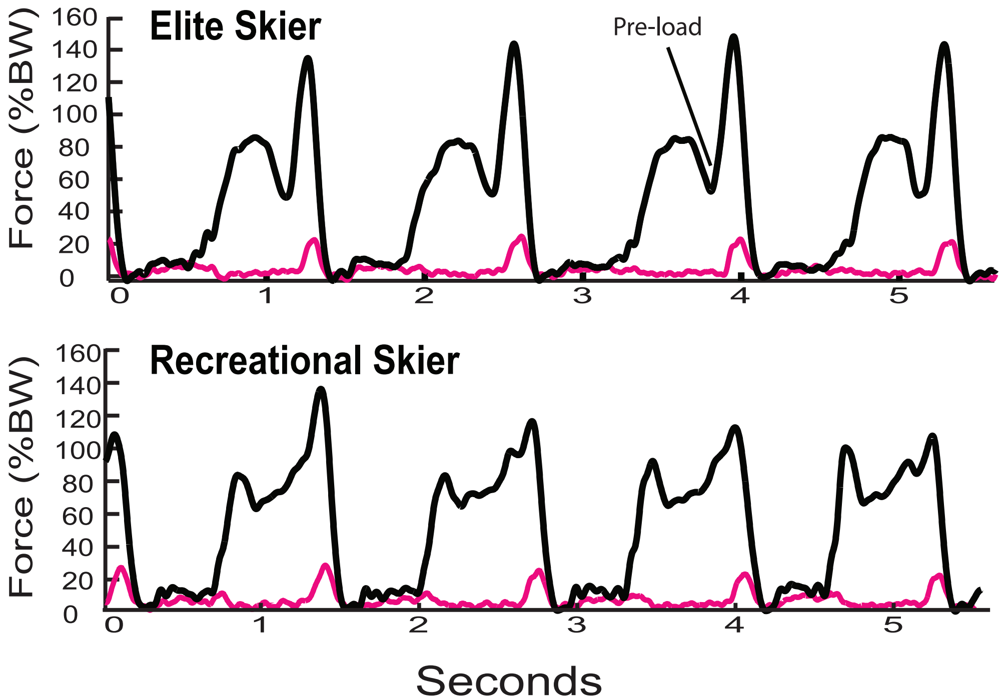

Figure 1.4. Force traces recorded from an elite skier and recreational skier. F_{perp} is shown in black, and F_{par} is shown in pink. The pre-load phase is only apparent in the elite skier's force traces.

	no incline	3 degrees	6 degrees
Pole 1.25 m/s			
Fpar (%BW)	3.43±0.59	5.90±0.51	9.82±0.52
Kick 1.25 m/s			
Fperp (%BW)	95.7±2.54	102±4.86	106±5.87
Pole 3 m/s			
Fpar (%BW)	4.99±0.37	5.67±1.05	10.2±1.18
Kick 3 m/s			
Fperp (%BW)	108±6.59	125±8.94	134±6.03
Fpar (%BW)	6.20±1.94	15.8±3.77	26.5±3.97

Table 1.1 Peak perpendicular and parallel forces for the pole and kick phases at 1.25 and 3 m/s. (means±SEM, n=9**).**

CHAPTER II

Mechanical Energy Fluctuations During Diagonal Stride Roller Skiing; Running on Wheels?

2.1 Introduction

Aerial and aquatic locomotion often involve power/glide cycles. For example, zebra finches use flap-glide cycles, rather than steady, repetitive flapping, to move through the air. Utilization of the flap-glide gait 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 jet/glide cycles (Marsh et al., 1992; O'dor, 2013). Because their 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, launching themselves and then gliding along the surface. Not only does this glide cycle allow water striders to move across water, but they can also reach speeds of up to 150 cm/s (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 belly and, with alternating foot movements, push themselves along the ice/snow surfaces. Penguins appear to save energy by tobogganing as opposed to walking (Wilson, 1991). Thus, power/glide locomotion can be rapid and efficient, as well as conserving energy and representing an appropriate adaptation to the environment.

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 therefore reduce the need for muscular power input (Cavagna et al., 1977). These two mechanisms inherently function based upon the braking and propulsion of the body during the repeated collisions with the ground. However, through the use of passive tools (skates, skis, wheels), 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 previously demonstrated for walking and running?

In this paper, we examined the fundamental center of mass 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. DIA is a technique that appears very similar to both walking at slow speeds and running at faster speeds while still incorporating a propulsive gliding element. Indeed, using kinematic analysis (Minetti et al., 2000) and (Pellegrini, 2011) have 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 center of mass (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 center of mass 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 center of mass (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 decreases and GPE increases. 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. Since 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). Traditionally, running was 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 without an aerial phase (Chang and Kram, 2007; McMahon et al., 1987; Rubenson et al., 2004). Thus, perhaps a better definition of running is a gait during which the COM is lowest during mid-stance (McMahon et al., 1987) and utilizes elastic energy storage and return.

In this study, we asked, are the center of mass mechanics of diagonal stride cross-country skiing just like walking and/or running but with an additional gliding/sliding phase? Or, do the COM mechanical energy fluctuations of DIA constitute a unique gliding gait? Based on the reports by Minetti et al. and Pellegrini, we hypothesized that running and DIA (but not walking) would have similar patterns of KE and GPE fluctuations. In other words, we hypothesized 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.

2.2 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, the gold-standard method is to 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 et al., 2011; Stöggl and Holmberg, 2011; Vahasoyrinki et al., 2008). However, to our knowledge, none have integrated the forces to calculate the center of mass energy fluctuations.

Experimental Protocol

We collected data for 9 subjects, 4 female, 5 male, (age: 26.3 ± 3.3 years, mass: 69 ± 9 kg, height: 175 ± 8 cm (mean±SD)). Subjects had an average of six years experience with cross-country skiing in the classic style, ranging in skill from recreational skiers 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 IRB approved protocol. We have previously reported on the ground reaction forces of DIA in this same group of subjects (Kehler et al., 2014).

Subjects walked (1.25 m/sec), ran (3.0 m/sec) and roller skied (1.25 and 3.0 m/sec) using the diagonal stride technique (DIA) on a custom-built force instrumented dual-belt treadmill (Franz and Kram, 2014) with a force platform mounted underneath the right belt. All subjects used PRO-SKI C2 Classic roller skis (Sterners, Dala-Järna, Sweden), their own ski boots, poles and running shoes. We replaced their pole tips with rubber tips (Holmberg et al., 2005). For safety, each subject wore a bicycle helmet and a waist belt that we secured to the ceiling with a slack rope (Fig. 2.1).

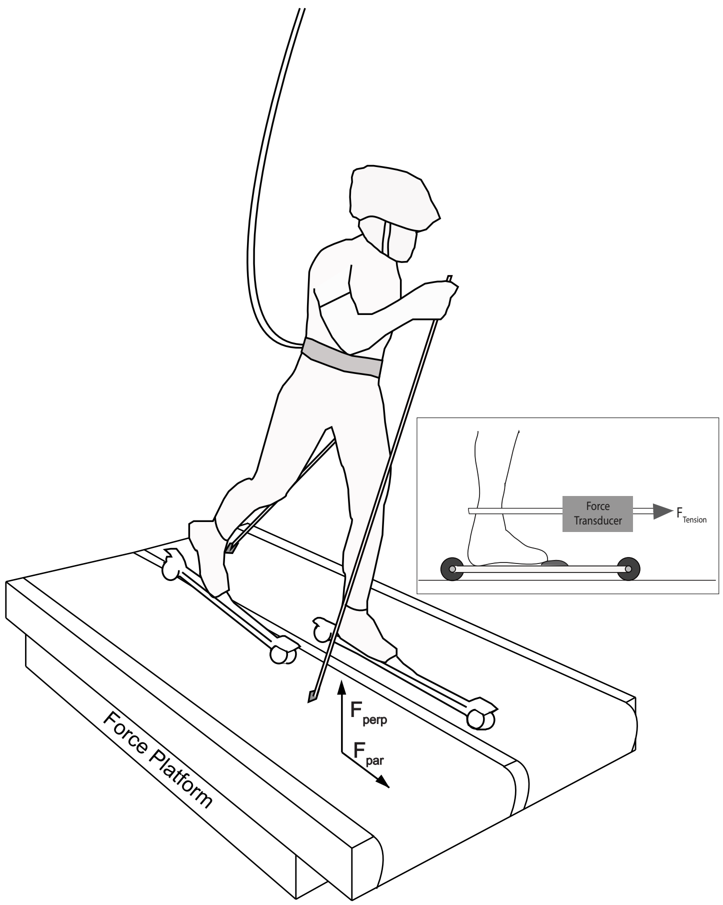

Figure 2.1. Experimental setup. Subject roller skiing on our custom-built, dual belt force instrumented treadmill. Device records parallel force (F_{par}) and perpendicular force (F_{perp}) from under the right side belt. Inset: Method for recording the rolling resistance of the roller skis.

To begin, participants warmed-up by roller skiing for at least 15 minutes to become comfortable on the treadmill. Further, this ensured that the roller ski wheels and bearings reached a proper temperature. Subjects then walked and skied at 1.25m/s and then ran and skied at 3m/s. All skiing trials utilized the diagonal stride technique (Smith, 1992).

Each trial of walking, running or skiing lasted two minutes with two minutes of rest in between.

Roller skiing trials were performed using four different configurations: 1.with one ski and one pole on each belt (split), 2. with the right pole only on the right belt and both skis and the left pole on the left belt, 3. with both skis and both poles on the right belt, and 4. with one ski on each belt, but no poles. These four configurations allowed us to 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 perpendicular (F_{perp}) and parallel (F_{par}) forces for 15 seconds at 1,000 Hz (LabView 8.0, National Instruments, Austin, TX, USA). After data collection, we filtered the walking and running GRF data using a recursive fourth-order Butterworth low-pass filter with a cutoff frequency of 25 Hz. Due to the lower stride frequency of roller skiing, we processed the roller skiing GRF data with a recursive fourth-order Butterworth low-pass filter with a cutoff 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. 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.

We measured the rolling friction of the roller skis by a towing test described previously (Sandbakk et al., 2010). We found the force required to tow a subject on the level force treadmill at 3 m/s (Fig. 2.1). The force was recorded by a force transducer

(Feedback Sports/ Alpine Digital Scale) and averaged over six trials. The mean μ value (0.027) was incorporated into later calculations.

Mechanical Energy Fluctuations

From the force recordings during DIA with and without poles (NP), we calculated the KE and GPE of the COM (Cavagna, 1975). The NP trials simplified the comparisons between walking, running and roller skiing. We custom-wrote a Matlab integration program modified for DIA and DIA NP. From the right belt force recordings, we created a composite force file that simulated combined left and right forces (Franz and Kram, 2013). From these force files, we used the technique developed by Cavagna (1975) 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 vertical to the treadmill belt. We calculated the perpendicular acceleration (a_{perp}) equal to (F_{perp}–mg)/m, where m is the participant's body mass and g is gravitational acceleration, 9.81ms^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. The instantaneous GPE was calculated as mgΔh.

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}- mg)/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 for the integration 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, $0.5mv^2_{result}$.

Statistics

We used Matlab to perform repeated-measures ANOVA with a Tukey's post-hoc analysis to find significant changes in peak forces and differences in magnitudes of fluctuation of the COM between different speeds and different modes of locomotion. All were analyzed with $P<0.05$ needed for significance.

2.3 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.

A few subjects ran with a mid-foot strike, rather than a heel strike, and their F_{perp} forces only had one peak (active peak). But for the subjects who ran with a heel strike, running F_{perp} forces exhibited two peaks, just like in walking. The impact peak had an average force of 145% (for heel strikers), and the second or "active" peak, which occurred at mid-stance, had averaged 218%BW. As expected, the patterns of running F_{par} forces were similar to those of walking, showing a negative braking peak and a positive propulsive peak. The averaged magnitudes of the braking and propulsive forces were -22%BW and 11%BW, respectively.

The vertical forces during each stride of diagonal stride roller skiing with (DIA) and without poles (DIA NP) (Fig. 2.2C,D) exhibited five general phases as identified previously (Vahasoyrinki et al., 2008). Our skiing stride was defined as starting with a 1) pole plant followed by a 2) glide phase of the ipsilateral roller ski. Next, there was a 3) pre-load phase when the F_{perp} decreased, as the COM is lowered, in preparation for the 4) 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 was not apparent in averaged force traces (Fig. 2.2). This sequence of force patterns was apparent in DIA NP (Fig. 2.2C) and DIA (Fig. 2.2D), although DIA NP obviously did not involve a pole plant force.

The kick F_{perp} values recorded for DIA NP at 1.25 and 3m/s were 87 and 122%BW respectively with corresponding values for DIA of 89 and 103%BW, respectively. The kick force in the parallel direction (F_{par}) for DIA NP was 11%BW for 1.25m/s and 16.5%BW for 3m/s. The F_{par} of DIA (Fig. 2.2D) indicated propulsive peaks associated with both pole contact and kick (4.3 and 5.7%BW, respectively, at 1.25m/s and 7.2 and 8.1%BW at 3m/s). From the pole only configuration, it was possible to determine the poling force (Fig. 2.2E) at 3m/s, but we could not resolve the small poling propulsive forces at 1.25m/s. The pole F_{perp} at 3m/s had a peak of 10.0%BW and the F_{par} peaked at 6.2%BW.

The ground reaction forces of walking, running and DIA NP can be easily compared at matched speeds (Fig. 2.2A,B,C). The F_{perp} in DIA and DIA NP were less than running because there is no aerial phase in DIA and DIA NP, and also less than the walking F_{perp} at

1.25m/s. The most important difference was the absence of any discernable negative, or braking, forces in DIA NP or DIA. That absence was of course due to the rolling of the skis themselves, which allowed the skiers to glide through the impact of the foot hitting the ground, rather than decelerating the body.

The mechanical energy fluctuations of the COM (KE, GPE and TE), calculated from the ground reaction forces, are depicted in Fig. 2. 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 nearly the same time point as the maximum of GPE and vice versa (Fig. 2.3A). Due to these opposite energy fluctuations, the total COM energy, TE (=KE+GPE) for walking fluctuated by only 0.21 J/kg (Table 2.1). DIA NP and DIA at 1.25 m/s exhibited more in-phase fluctuations of KE and GPE; with the KE and GPE minimums both occurring at the initiation of the kick. The TE during DIA fluctuated by 0.30 J/kg, whereas the corresponding value for DIA NP was 0.74 J/kg, which was significantly different than the magnitude of walking TE fluctuations (Table 2.1).

The COM mechanical energy fluctuations for running are shown in Fig. 2.3. As expected, the COM during running had energy fluctuations that were in-phase. Both KE and GPE reached their minimum during mid-stance phase. Due to the inability of the force platform to record elastic energy, the so-called TE of running fluctuated by 1.48 J/kg (Table 2.1). At 3 m/s, DIA NP and DIA also exhibited in-phase fluctuations of KE and GPE. The KE and GPE minimums occurred almost simultaneously at the initiation of the kick and as a result the TE fluctuation was substantial, averaging 0.73 J/kg for DIA NP and 0.55 J/kg for DIA.

In Figure 2.4, we highlight the KE of DIA NP at 3 m/s. KE initially increased throughout the kick, as the subject's COM accelerated forward, and then KE steadily decreased throughout the glide phase. We calculated the rate of decrease in energy 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 seconds. Therefore, there were 0.41 seconds for the KE to decrease by an average of 0.32 J/kg. The overall calculated rate of decrease in KE during the glide was thus -0.78 W/kg. Where does this 0.78 W/kg go? Was it stored elastically or dissipated as frictional heat?

We found 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. Since power equals the product of force and velocity, at 3m/s, this results in a power of 48.6 W. Normalized to body mass, the roller skis dissipated 0.70 W/kg to friction during the glide phase.

2.4 Discussion

Although we used a different methodology, the general shapes of the roller skiing ground reaction forces were comparable to traces previously reported for on snow skiing (Komi, 1987; Vahasoyrinki 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 is decreasing and vice versa. Since these two mechanical energies exchange through the inverted pendulum method, the TE fluctuates by a lesser magnitude. We compared walking with DIA NP at 1.25 m/s, which is a normal walking speed. When the COM fluctuations of walking and DIA NP are side –by – side (Fig. 2.3), it is clear that DIA NP does not share the same patterns as walking. The KE and GPE of the center of mass are out-of-phase in walking and these same mechanical energies in DIA NP skiing appear more in-phase, if anything, with the KE and GPE fluctuating together, not opposite. Moreover, compared to walking, the TE of DIA NP has a significantly larger magnitude of fluctuation. Thus, our results concur with Pellegrini (2011) regarding walking vs. DIA. Also, the COM of walking reaches its highest point during single leg stance. However, the COM of DIA NP and DIA is actually lowest during the middle of stance phase at 1.25m/s, so slow DIA is clearly not biomechanically similar to walking on this additional count.

As hypothesized, the mechanical energies of DIA NP and DIA appear more similar to running, which has in-phase fluctuations of KE and GPE. The minimum KE and GPE occur at the same point during a running stride (Fig. 2.3). DIA NP has almost in-phase fluctuations of KE and GPE (Fig. 2.3 and Fig. 2.4) with the minimum KE occurring at nearly the same time as the minimum GPE. Also, during mid-stance, the COM is at its lowest point during both running and DIA at 3m/s. Due to these observations, we agree with previous statements that indeed, running and DIA have biomechanical similarities.

Based on the spring-mass system, the stance leg acts as a spring, which can store and return energy with each step. In running, the mechanical energy fluctuations are symmetrical, so 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 muscles and tendons of the stance leg to be mechanically 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 slight recovery of GPE from elastic energy stored in the tendons. In fact, through angular analysis it has been previously concluded that there is elastic energy storage of GPE possible due to the pre-stretch of the preload phase of DIA (Komi and Norman, 1987).

However, running is an economical mode of locomotion because it can also store KE as elastic energy, not just GPE. For each step in DIA, muscular energy is required to kick and move the ski into glide. But then, the kinetic energy decreases throughout the glide phase, as the energy put in to the system is lost (Fig. 2.4). During the glide phase of DIA, almost all of the KE inputted for each step is dissipated (as friction) and therefore cannot be stored and returned. We calculated that 89.7% of the inputted power is lost due to rolling resistance and therefore could not be stored within the stance leg as elastic energy. We conclude that running and DIA are fundamentally different in their energy recovery methods, and DIA should not be explained by a spring mass model.

An interesting result of this study, and a possible area of future study, is the effect of using poles. We found that when the poles are used for DIA, the KE fluctuations become smoother and as a result, so do the TE fluctuations. The smoother fluctuations of the KE are still more in-phase, like running, but the overall loss of KE during the glide phase is less. It seems that a function of the pole is maintain a constant forward velocity, rather than slowing down during each glide phase. Poles appear to counteract the effects of friction on the roller skis. This raises the question of pole optimization. Does skillful use of poles produce a more mechanically and metabolically economical skiing technique?

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

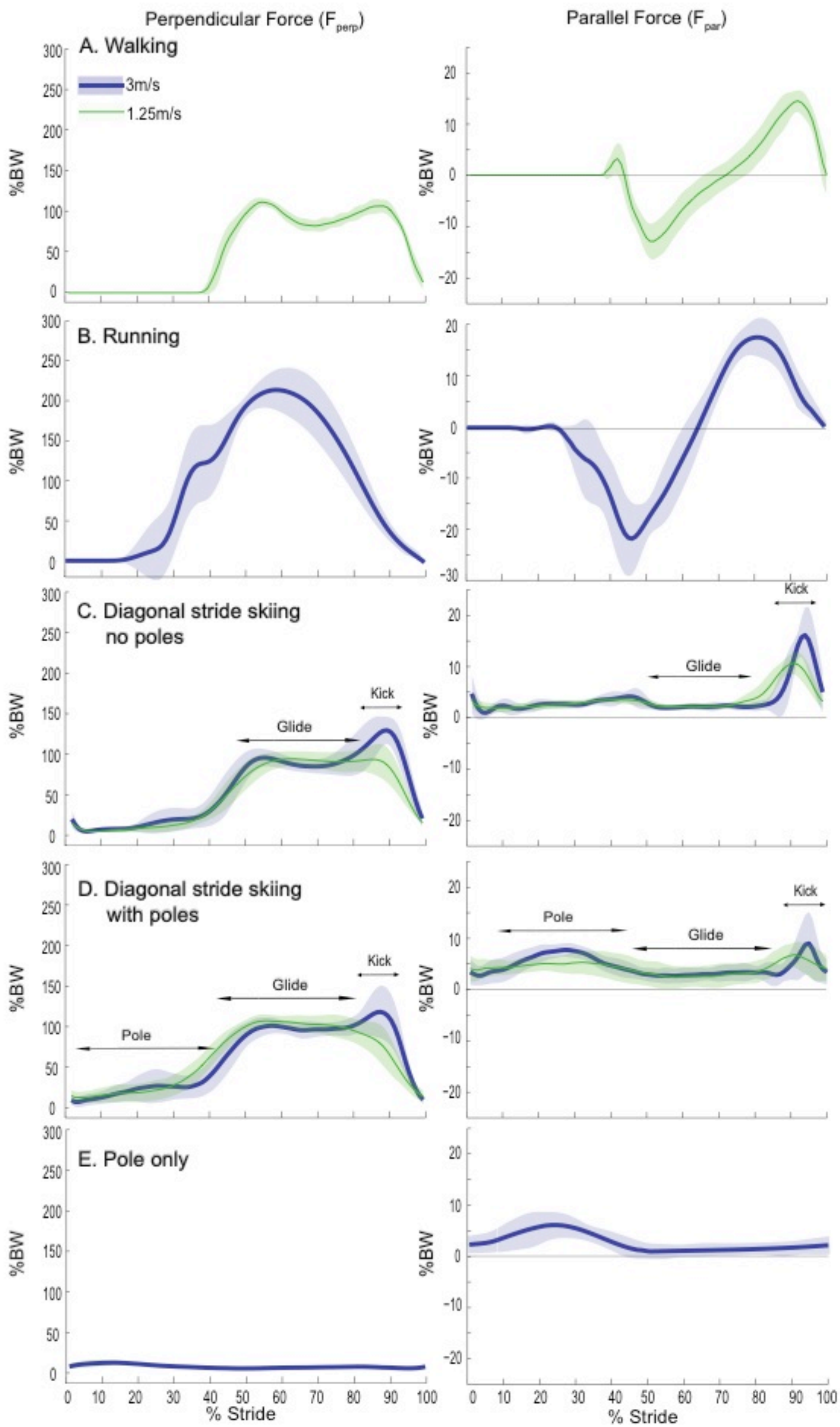

Figure 2.2 Perpendicular and parallel forces averaged from all subjects ± shaded standard deviation from A. Walking at 1.25 m/s B. Running at 3m/s C. diagonal stride roller skiing without poles at both speeds D. diagonal stride roller skiing with poles at both speeds E. just right pole at 3 m/s (could not resolve pole forces at 1.25m/s). Forces are normalized to body weight (BW) and % stride begins and ends with toe off or pole plant.

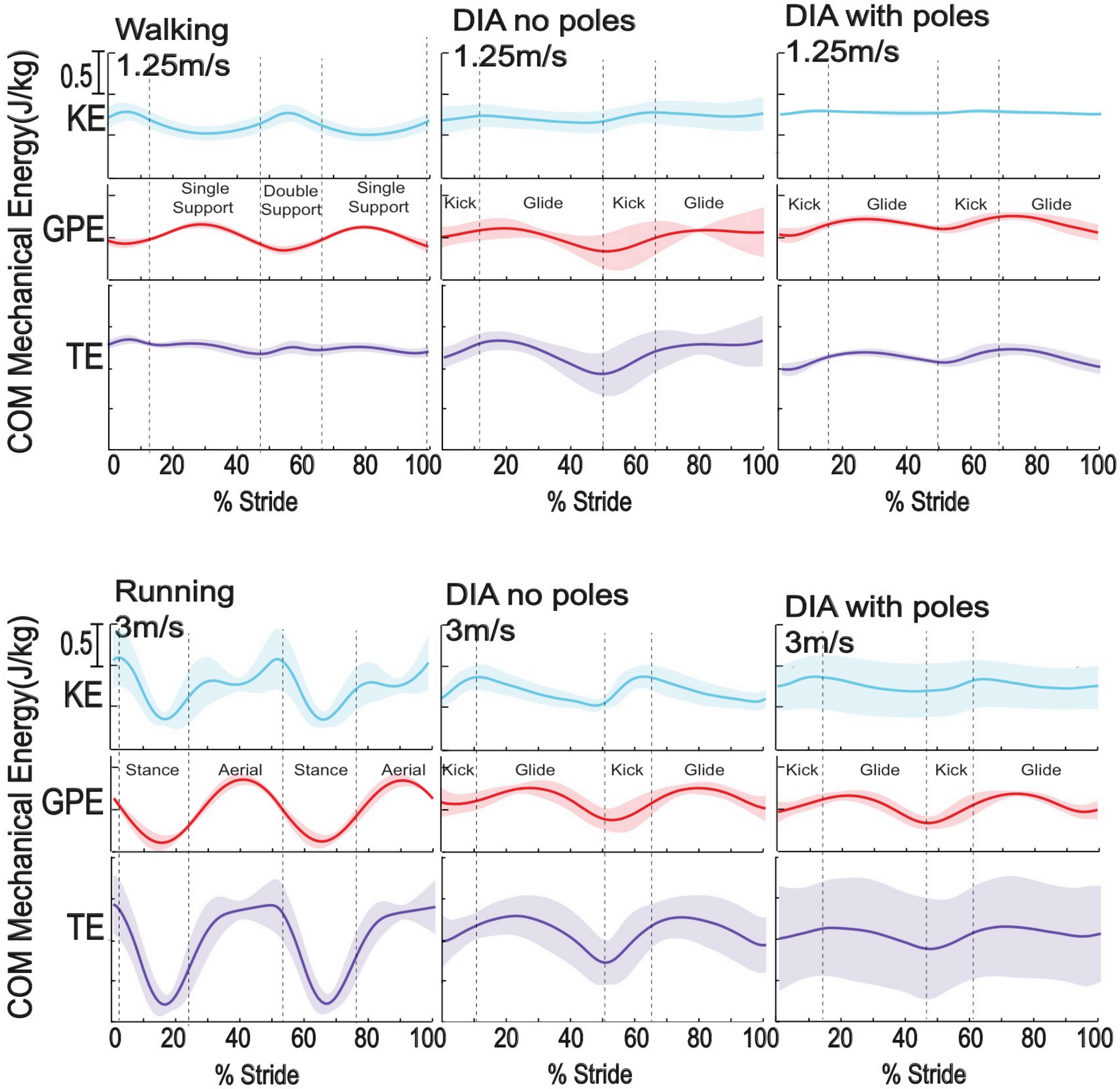

Figure 2.3. Mechanical energy fluctuations of the center of mass for walking, running, and diagonal stride roller skiing with and without poles at 1.25 m/s and 3m/s. Kinetic energy (KE), gravitational potential energy (GPE), and total energy (TE) are normalized to bodyweight (J/kg) and a stride begins and ends with subsequent ipsilateral heel strikes or roller ski plant.

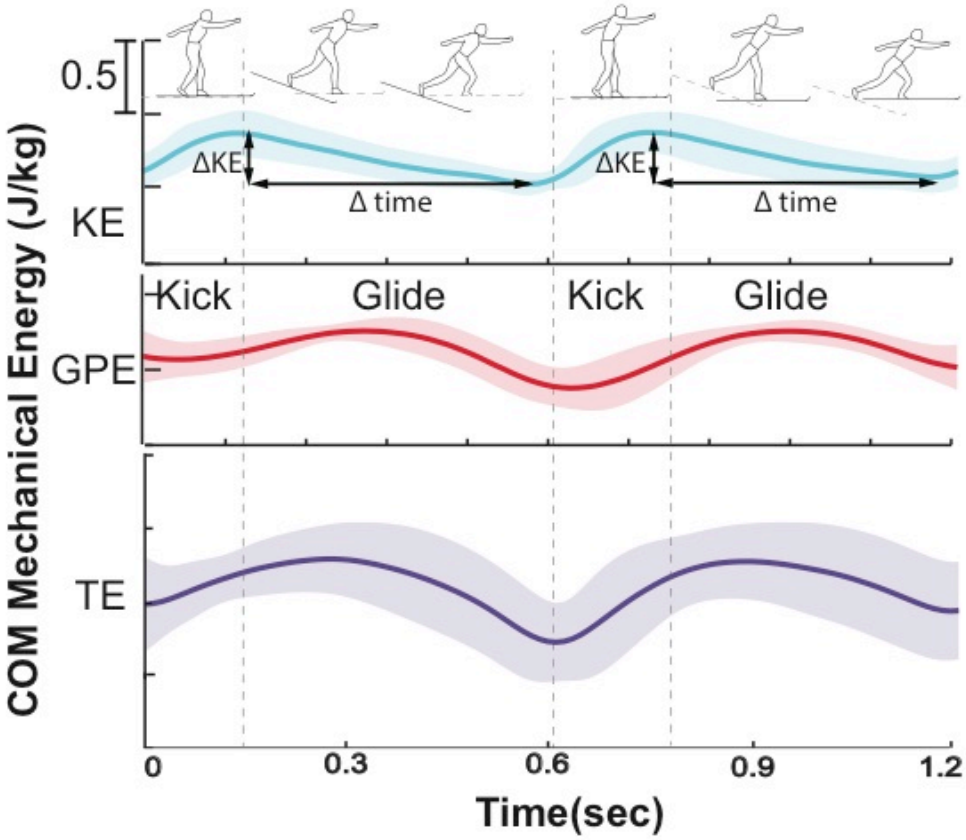

Figure 2.4. Mechanical energy fluctuations of no pole diagonal stride roller skiing (NP DIA). Each curve is the average of all subjects ± a shaded standard deviation. Kinetic energy (KE), gravitational potential energy (GPE), and total energy (TE) are measured in J/kg. Black arrows show how the change in the rate of kinetic energy (ΔKE/Δtime) decrease during the glide phase was calculated.

	Walk 1.25 m/s	DIA NP 1.25 m/s	DIA 1.25 m/s
ΔKE (J/kg)	0.30±0.03	0.19±0.02*#	0.08±0.01*#
ΔGPE (J/kg)	0.34±0.02	0.54±0.11#	0.27±0.04#
ΔTE (J/kg)	0.21±0.03	0.74±0.13*#	0.30±0.05#

	Run 3m/s	DIA NP 3 m/s	DIA 3 m/s
ΔKE (J/kg)	0.97±0.12	0.41±0.05*	0.37±0.12*
ΔGPE (J/kg)	0.78±0.06	0.53±0.05*	0.45±0.09*
ΔTE (J/kg)	1.48±0.1	0.73±0.07*	0.55±0.16*

Table 2.1. Magnitudes of mechanical energy fluctuations of the COM presented in figure 2 (means±SEM, n=9**).** Statistical comparisons were run between the 3 modes of locomotion at each speed (1.25 and 3 m/s). * significantly different from walking or running at the same speed, # significantly different between poles and no poles.

CHAPTER III

Energetic cost of Gliding, Walking, and Running: Do Poles Help or Hinder?

3.1 Introduction

Passive tools, like cross-country skis, allow humans to locomote faster, farther and more economically (Minetti, 2004). Long distance cross-country (XC) skiers can cover over 129 more km per day than long distance runners, and top skiers can maintain paces for 10km that would exhaust world class runners within the first 5 minutes (Bellizzi et al., 1998). Because it allows gliding, XC skiing intuitively seems like it would require less energy than walking or running. However, MacDougall reported that the energetic cost of XC skiing with the diagonal stride technique on level surface was 10-12 ml/kg/min greater than that predicted for running at the same speed (MacDougall et al., 1979). In contrast, when compared to known running values, Saibene et al. (1989) found that at a range of speeds (3.75 to 8 m/s), diagonal stride skiing can be much less expensive in $\dot{V}_{O2}$ (Saibene et al., 1989). However, neither study directly compared the metabolic cost of running and skiing in the same subjects. Similarly, to our knowledge, no previous study has directly compared the energetics of walking and skiing in the same subjects either. Thus, in the present study we compared the metabolic cost of walking, running and diagonal stride skiing at matched speeds in the same subjects.

Diagonal stride classic XC skiing (DIA) appears similar in form to walking and running, but of course, in DIA skiers typically use poles for balance and supplemental propulsion. Poles are a defining characteristic of XC skiing and would seem to provide biomechanical and energetic advantages during DIA. When the upper body and legs work together, the peak oxygen uptake is higher and the metabolic cost of DIA is less than skiing with just legs or just poles (Holmberg and Calbet, 2007).

In a previous study (Kehler et al. 2014), we analyzed the mechanical energy fluctuations of the center of mass (COM) during DIA and DIA without poles (NP). We found that when poles were used for DIA, compared to DIA NP, the kinetic energy of the COM fluctuated by a lesser magnitude, or became "smoother". As a result, the total energy (kinetic energy + gravitational potential energy) of the COM also fluctuated less. Thus, it seems a function of the pole is to maintain a more constant forward velocity, by adding propulsion in between ski kicks. Poles counteract the effects of rolling resistance or sliding of the roller skis or snow. Do the biomechanical advantages of poles translate into metabolic savings?

The metabolic effects of poling have been investigated previously. Belizzi et al. (1998) measured the energetic cost of DIA roller skiing with legs only and arms only on a treadmill at a 1.5° incline, but did not directly compare to arm-and–leg DIA (Bellizzi et al., 1998). From their results, we calculated that the metabolic rate of not using poles during DIA was 5% greater. Overall, they found that the energetic cost of DIA is set by the generation of force to support the weight of the body and to overcome friction. Since the poles are tools used to counteract friction during the glide of the ski, providing propulsive force with the poles can reduce the energetic cost of skiing. More recently, Sandbakk et al. compared oxygen uptake during XC skiing in the Gear 3 skating technique with and without poles (Sandbakk et al., 2013). They found that at a submaximal speed, the rates of oxygen uptake were approximately 10% less when using poles.

Our purpose was to compare the energetic cost of walking and running to diagonal stride cross-country skiing at matched speeds and to determine the energetic cost/benefit of using poles for diagonal skiing. We hypothesized that at matched speeds, diagonal stride skiing would consume less energy than walking and running respectively. We also hypothesized that not using poles during diagonal stride skiing would increase the energetic cost.

3.2 Methods

We collected data for 9 subjects, 4 female, 5 male, (age: 26.3 ± 3.3 years, mass: 69 ± 9 kg, height: 175 ± 8 cm (mean±SD)). Subjects had an average of six years experience with cross-country skiing in the classic style, ranging in skill from recreational 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 IRB approved protocol. We have previously reported on the biomechanics of DIA in this same group of subjects (Kehler et al., 2014).

Subjects walked (1.25 m/sec), ran (3.0 m/sec) and roller skied (1.25 and 3.0 m/sec) using the diagonal stride technique with poles (DIA) and with no poles (DIA NP) on a custom-built force instrumented dual-belt treadmill (Franz and Kram, 2014). All subjects used PRO-SKI C2 Classic roller skis (Sterners, Dala-Järna, Sweden), their own ski boots, poles and running shoes. We replaced their pole tips with rubber tips (Holmberg et al., 2005). For safety, each subject wore a bicycle helmet and a waist belt that we secured to the ceiling with a slack rope (Fig. 3.1).

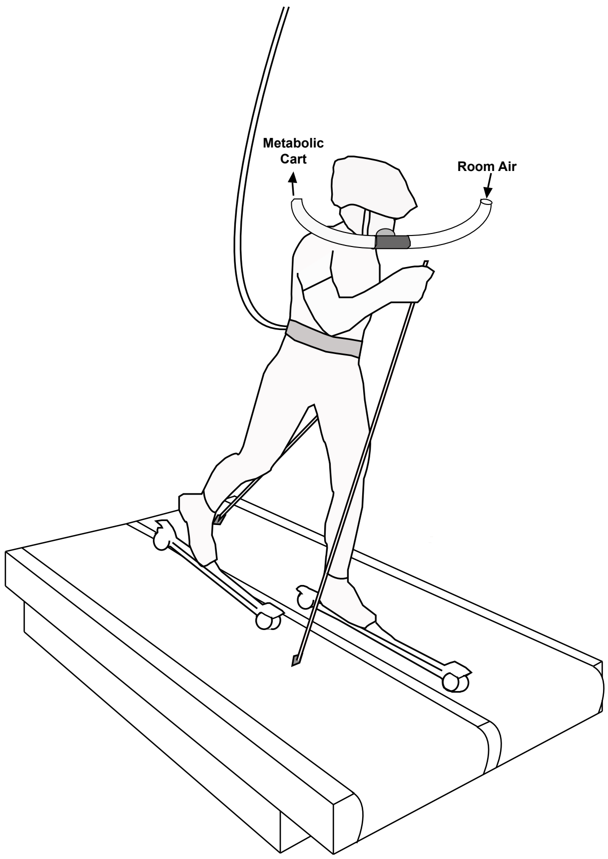

Fig. 3.1. Subject roller skiing on the dual belt treadmill while we analyzed their expired gases to determine energy expenditure. Subject breathes in room air through a tube on the left side and exhales through a tube on the right, which is connected to a Parvo Medics expired gas analysis system. We determine their rates of oxygen consumption ($\dot{V}_{O2}$) and carbon dioxide production ($\dot{V}_{CO2}$).

To begin, participants warmed-up by roller skiing for at least 15 minutes to become comfortable on the treadmill. Further, this assured that the roller ski wheels and bearings reached a proper temperature. Subjects then walked and skied at 1.25m/s and then ran and skied at 3m/s. All skiing trials utilized the diagonal stride technique (Smith, 1992). All walking and roller skiing trials were performed across the split of the treadmill, with each leg on a separate belt. Running trials were performed on just one treadmill belt.

Energy Measurements

We measured the rates of oxygen consumption ($\dot{V}_{O2}$) and carbon dioxide production ($\dot{V}_{CO2}$) using an open-circuit expired gas analysis system (Parvo Medics). Before beginning the experimental trials, we measured the standing metabolic rate, as a baseline. All trials were 5 minutes long, and we determined the average $\dot{V}_{O2}$ (ml O_2/s) and $\dot{V}_{CO2}$ (ml CO_2/s) for the last 3 minutes of each trial. Our metabolic software calculated metabolic rate (W/kg) using a standard equation (Brockway, 1987).

The cost of transport for each mode of locomotion (J/kg/m) (i.e. the mass-specific metabolic energy expended to move a unit distance) was calculated by dividing gross mass-specific metabolic rates by the speed of the specific trial (Weyand et al., 2010).

Stats

We used Matlab to perform paired T-tests to analyze differences in metabolic rates between conditions with $p<0.05$ needed for significance.

3.3 Results

We measured the gross metabolic rate of walking at 1.25 m/s to be 4.27 W/kg (±0.20SEM), averaged for all subjects. The metabolic rate for DIA at 1.25 m/s was 5.42 W/kg (±0.27SEM). Therefore, DIA at 1.25 m/s required 27% more metabolic power than walking (p=.013). Seven out of the nine subjects used less metabolic energy while walking vs. DIA. The costs of transport for DIA and walking at 1.25 m/s were 4.34 and 3.42 J/kg/m, respectively. The average standing oxygen consumption was 4.77 mlO_2/kg/min (±0.39SEM) (metabolic power = 1.62 W/kg).

DIA and running at 3 m/s were also significantly different in terms of metabolic power (p=0.0042). Running required 19.1% more metabolic power than DIA at 3 m/s. The gross metabolic rates for running and DIA at 3 m/s were 12.4 W/kg (±0.38SEM) and 10.41

W/kg (±0.37SEM) respectively (Fig.3.2). All nine subjects used more energy to run than to ski and the costs of transport for DIA and running at 3 m/s were 3.47 and 4.12 J/kg/m, respectively.

Surprisingly, compared to normal DIA skiing with poles, at both 1.25 and 3.0 m/s, skiing without poles did not significantly increase the metabolic power required ($p = 0.35$) (Fig. 3.3). The metabolic rates for DIA NP at 1.25 m/s and 3 m/s were 5.57 W/kg (±0.25SEM) and 11.1 W/kg (±0.72SEM). The cost of transport was greater when the poles were removed at both speeds. At 1.25 m/s the cost of transport increased by 2.8% when skiing without poles (4.34 J/kg/m for DIA and 4.46 J/kg/m for DIA NP) and at 3 m/s it increased by 6.62% (3.47 J/kg/m for DIA and 3.7 J/kg/m for DIA NP).

3.4 Discussion

In contrast to our hypothesis, DIA was more energetically expensive than walking at 1.25 m/s. DIA is not a technique normally employed by racers at such slow speeds, but many recreational skiers surely ski within that speed range. However, at 1.25 m/sec, the force contribution of the poles is very small (Kehler et al. 2014), so poles may be just adding weight rather than acting as a propulsive aid. However, in support of our hypothesis, at 3.0 m/sec, DIA had a significantly lower metabolic rate than running ($p=0.0042$). Runners have braking phase in which their horizontal velocity slows down, but in DIA roller skiing, no negative or braking forces were detected (Kehler et al. 2014). The absence of braking forces means that the roller ski glides through the collision with the ground and therefore does not lose much speed initially. This reduces the cost of applying ground reaction forces which were shown to be directly linked to energy expenditure

(Bellizzi et al., 1998). Therefore, we partially accept our first hypothesis comparing the metabolic rates of DIA, walking and running.

In contrast to our second hypothesis, at both speeds, the use of poles provided no statistically significant metabolic savings. At 1.25 and 3 m/s, the metabolic rate increased slightly in 6 of 9 subjects when the poles were removed. The lack of an energetic advantage between pole and no pole conditions could be due to the fact that all tests were done on a level surface. As has been previously shown by Bellizzi (1998) and in another of our studies (Kehler et al. 2014), the propulsive forces of the poles significantly increase on steeper inclines. Perhaps there would be a larger metabolic effect of pole removal on inclines. It has been shown that during DIA, oxygen extraction is lower in the arms than in the legs at submaximal intensities, so the arm contribution to overall metabolic rate is small (Bjorklund et al., 2010).

The cost of transport values recorded for all locomotion modes were calculated from the gross metabolic values and treadmill velocity. The lowest cost of transport was walking, followed closely by DIA at 3 m/s. So for long distance travel, walking would be the most cost efficient. However, if using the diagonal stride skiing technique, skiing at the faster speed of 3 m/s would be less costly than 1.25 m/s. In fact, even skiing at 3 m/s without poles would be more cost efficient than using DIA at 1.25 m/s.

In the future, we could expand upon the current study by including metabolic measurements of inclined DIA and DIA NP as well as compare them to walking and running at the same speeds. Also, by increasing the subject pool, we might detect possibly a significance would arise between pole and no pole conditions.

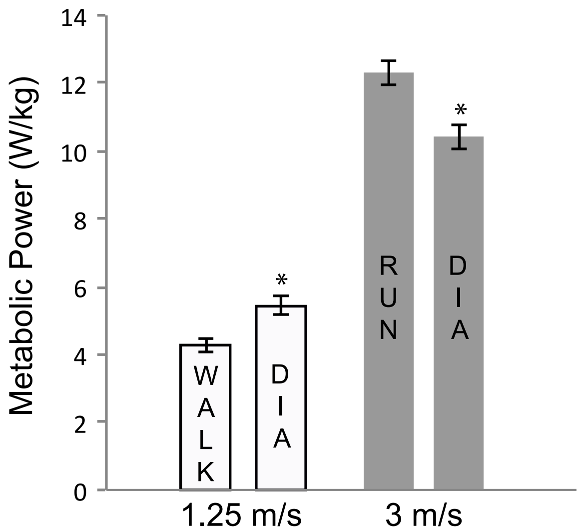

Fig. 3.2. Metabolic power in W/kg for walking, running and diagonal stride skiing (DIA) at 1.25 and 3 m/s. Error bars are SEM (W/kg). Asterisk (*) represents a significant difference (p<.05) between modes of locomotion at matched speeds.

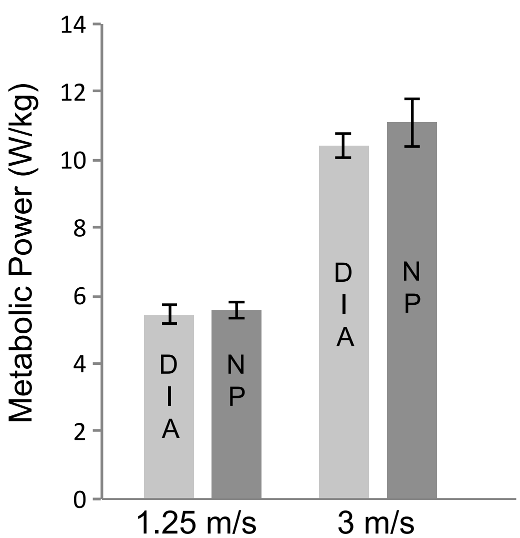

Fig. 3.3. Metabolic power for diagonal stride skiing with poles (DIA) and diagonal stride skiing without poles (DIA NP) at 1.25 and 3.0m/sec. Error bars are SEM (W/kg). The removal of poles did not significantly increase the metabolic power required (p=0.35).

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