

THE EFFECT OF LOWER LIMB LOADING ON ECONOMY AND KINEMATICS
OF SKATE ROLLER SKIING

by

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ABSTRACT

It has been proposed that skate skiing economy and racing performance have improved as a result of lighter equipment. Despite the many studies that have found running and walking economy to improve with lighter shoes, there are no published studies that show any relationship between the mass of skate skiing equipment and markers of skate skiing performance. To investigate the effects of skate skiing equipment mass on markers of performance, this study added mass to the lower limbs of skate roller skiers and measured changes in economy and gross movement kinematics. Twelve male (Mean±SD; Age (yrs): 21.4±3.9) and eight female (Mean±SD; Age (yrs): 19.9±2.2) competitive cross-country skiers completed two laboratory visits to roller ski on an oversized treadmill. In the first visit, subjects completed a graded exercise test to determine their lactate threshold. In the second visit, subjects completed 5 minutes of roller skiing at a low work rate (2 m/s for women and 3 m/s for men both at 2°) and a high work rate (2 m/s for women and 3 m/s for men both at 3.15°) for each of the four limb loading conditions (0 g, 200 g, 400 g, and 600 g). Oxygen consumption (VO_2), heart rate (HR), and cycle rate were measured during the last 2 minutes of each stage and used for analysis. There were no significant differences in HR, VO_2 , or cycle rate between any of the limb loading conditions at either work rate. However, cycle rate neared significance ($P = 0.06$), with increases in cycle rate observed during greater limb loading. Interestingly, VO_2 and HR significantly increased throughout testing, independent of limb loading condition. The most notable increases were observed in HR values, and increases began within the very first testing stage. Thus, it is likely that the subjects experienced cardiovascular drift due to mild hyperthermia. The effects of hyperthermia might have masked the true effects of lower limb loading. Therefore, future studies still need to investigate the effects of lower limb loading on skate skiing economy and kinematics.

1. INTRODUCTION

In the late 1980s, cross country ski manufacturers began developing equipment that was specifically designed for skate skiing. Since then, the design of skate ski equipment and the manufacturing materials have continually evolved. For example, the material composition of skis, boots, and poles have changed to lighter materials. Specifically, the plastic soles and cuffs of skate ski boots, the wood cores of skis, as well as fiberglass ski pole shafts have all been replaced, primarily with carbon fiber. As a result, the use of modern materials within elite-level equipment has greatly decreased the mass of modern cross country ski equipment.

Complementing the evolution of ski equipment is the ever-increasing speeds observed in Nordic ski racing. For example, 10 km skate ski race times decreased by 27.4% from the 1985 World Championships to a 2012 World Cup race (31.0 minutes in 1985 to 22.5 minutes in 2012; fis-ski.com 2013). While skiing times are each affected by varying snow conditions and course profiles, these two times are representative of a typical time to complete the 10 km during the respective race seasons. Certainly, advances in training programs and sports nutrition have contributed to some of this improvement. However, if training and nutrition were the primary causes of this change, then similar time improvements would be expected in other endurance sports. For example, the 10 km run is an endurance-based competition with similar metabolic demands to Nordic skiing, so improvements in race times due to training and nutrition advances should be comparable over the same time period. However, the winning time in the 10,000 m run on the track at the 2012 Olympics was only 1.0% faster than the

same event at the 1984 Olympics (27:30.42 in 2012, 27:47.54 in 1984), which indicates that additional factors have contributed to the improvement in Nordic ski race times (Olympic.org 2013). Among the proposed factors that have added to the increased speed in Nordic skiing are improvements in trail grooming, ski waxing, and equipment (Street 1992). Although Street (1992) postulated that the decreased mass of ski equipment likely contributed to the incredible improvement in ski race times, no studies have evaluated the relationship between Nordic ski equipment mass and skiing performance.

A study addressing equipment mass be useful from a historical perspective, and it would also be useful for evaluating current equipment. A common claim by ski equipment manufacturers is a reduction in equipment mass between generations. Ski equipment generally gets lighter with each generation, but it is unknown how much of a decrease in mass is needed to impact performance. For example, the elite line of skate ski boots for one company will drop about 450 g when their new skate boots become available during the 2013-2014 ski season (from the S-Lab Pro, 1300 g, to the Carbon Skate, approximately 850 g; A. Gerlach, personal communication). Additionally, other ski companies have recently reduced the mass of their equipment. For example, much of the elite equipment unveiled for the 2010-2011 season was lighter according to the gear review published in Cross-Country Skier magazine (Cross-Country Skier Magazine 2010). Specific mass decreases included 175 g from Rottefella's top line of bindings, 160 g from Atomic's Featherlight World Cup skis, and 200 g from Rossignol's Xium World Cup skate boots (all reductions per pair). Similarly, differences in mass exist between many entry level packages and elite racing packages. For example, a skate ski

package could weigh approximately 3000 g (Fischer CRS 187 cm skis, Salomon Pilot Equipe bindings, and size 42 Salomon S-Lab Pro boots; rei.com 2013; Salomon Nordic 2012). In contrast, another option for the same skier could weigh 2260 g (Fischer Carbonlite RCS 187 cm skis, Rottefella Xcelerator bindings, and size 42 Rossignol Xium WC boots; rossignol.com 2013; skinnyskis.com 2013). Whether or not this 740 g difference would significantly affect skiing performance is unknown.

Load Carriage

It has been documented that additional mass added to the body increases the energy required to move. At submaximal activity levels, the energy expended to move can be calculated by measuring oxygen consumption, and a person's oxygen consumption required to move at a set absolute work rate has been termed "economy" (Cavanagh & Kram 1985a). The extent to which load carriage impacts economy depends not only on the amount of mass added, but also the placement of the mass. Additional mass placed on the torso will cause a relative increase in oxygen consumption (VO_2) directly proportional to the relative increase in total mass (Taylor et al. 1980). As the mass is placed more distally (e.g., on the lower extremity), the effect on VO_2 increases substantially. The larger VO_2 increase is caused, in part, by the greater distance traveled by any given point on the lower extremity than the torso. In the case of skis, bindings, and boots, the mass not only has to be moved forward with the skier's center of mass, it also must be moved laterally with every leg push during skating. Another reason greater VO_2 changes are observed when mass is added more distally is because of the effect mass

has on torque requirements. In skate skiing, every stride consists of accelerating the leg about the hip axis using a forceful abduction phase followed by a swing adduction phase to return the leg to a neutral position. According to the rotational component of Newton's second law of motion, the torque required to create angular acceleration is proportional to the moment of inertia of the object (the leg and equipment), which is exponentially related to the radius from the axis (hip joint). Hence, as a load is placed more distally on the limb, the torque necessary to accelerate the limb will increase exponentially. Because more torque is required during each stride when the limb is loaded, the leg muscles must generate more force, and thus expend more energy, for a given rate of limb movement.

Many researchers have documented increases in energy expenditure due to limb loading while running (Divert et al. 2008; Franz, Wierzbinski, & Kram 2012; Jones et al. 1984; Martin 1984; & Myers & Steudel 1985). The researchers have all found that VO_2 increases by between 0.9 - 1.5% for every additional 100 g on each foot. Since these studies have found very similar findings despite using a variety of subject populations, it is unlikely that other variables such as gender, length of the lower limb, and amount of muscle mass on the lower limb substantially change the effect of limb loading on running economy. A similar effect is expected in Nordic skiing because Stöggl & Müller (2009) noted that skiing and running have similar energetic demands and neural patterns. Adding a load to the upper extremity during walking has also been found to increase energy expenditure (Hendrickson, Porcari, Terry, Walsko, & Walter 1997; Rodgers, VanHeest, & Schachster 1995). In each study, VO_2 increased while walking with poles

compared to walking without poles. Adding mass in the form of poles to the hands is similar to adding mass to the lower extremity in the form of Nordic skis because the mass is located beyond the most distal point of the limb. Given the research on running shoes and hiking poles, it is reasonable to assume that a similar relationship exists between the amount of added mass on the lower limb and increases in energy expenditure during Nordic skiing. However, no published studies are available to verify that a similar relationship exists.

Interestingly, a pilot test of limb loading for one subject during skate roller skiing indicated that the effect of added mass on skate roller skiing economy may be smaller than what has been documented in running. Specifically, the subject consumed 1% more VO_2 for 500 g of added mass per foot. This is in contrast to research on running, which has consistently found that the addition of only 100 g per foot will cause a 1% increase in VO_2 . Clearly, there might be a difference in the effect of limb loading in skate skiing compared to running. It is possible that runners are more sensitive to limb loading because the foot is lifted higher off the ground during a running stride compared to a skate skiing cycle. Further, stride rates used during running are typically faster than the cycle rates used in skate skiing because skiers can utilize glide to increase their cycle length, whereas runners cannot. The faster rate of limb movement in running might cause a greater effect of lower limb loading on running economy compared to skate skiing economy. However, a full study is necessary to investigate the relationship between added mass on the foot and economy of skate skiing.

Load carriage on the limbs while Nordic skiing is also likely to influence gross skiing kinematics, such as cycle length and cycle rate. These movement kinematic variables are of importance because many researchers have found that the cycle rate and/or cycle length used by skiers while racing are correlated to their skiing velocity (Andersson et al. 2008; Bilodeau et al. 1996; Millet et al. 1998; Rundell & McCarthy 1996; Sandbakk et al. 2011; Stöggl & Müller 2009). Further, Sandbakk et al. (2011) found a correlation between the cycle rate used during submaximal roller skiing and performance in ski races. Cycle rate and cycle length are theorized to be affected by limb loading because limb loading has been found to influence gross running kinematics. For example, several researchers have documented that an increase in the mass of a runner's shoes led to decreased stride rate (Divert et al. 2008; Lussiana, Fabre, Hebert-Losier, & Mourot 2013). Since both running and skiing involve a stride cycle consisting of accelerating the foot in opposing directions, including both a propulsive and a swing phase, it is possible that limb loading will similarly affect stride rate (i.e., cycle rate) in skiing. However, there are no published studies documenting the effect of added mass on cycle rate or cycle length in Nordic skiing.

Limb Velocity

The effect of additional limb mass on economy and movement kinematics of skate roller skiing might vary with the skier's cycle rate. For example, it was noted earlier that a substantial portion of the energy required to move is devoted to accelerating the limbs, and that small changes in mass on the distal point of the limb will greatly

impact the force required to cause the acceleration. Myers & Steudel (1984) supported this conclusion and calculated that the proportion of energy devoted to swinging the limbs substantially increases with increased limb velocities. Increases in cycle rate are responsible for these changes in limb velocities because a faster cycle rate forces the limbs to complete a similar range of motion in a shorter amount of time. Therefore, it might be beneficial to investigate the effects of limb loading at two different cycle rates, so that researchers can investigate whether an interaction exists between cycle rate and added mass on economy.

In previous studies, cycle rates have been shown to change with work rate (Lussiana et al. 2013; Stöggl & Müller 2009). While it is possible that cycle rate will vary slightly with altered limb loading, the changes in cycle rate are expected to be small relative to the changes associated with changing work rate. For instance, Lussiana et al. (2013) found that increasing the mass of running shoes by 146 g per foot caused stride rate to decrease by approximately 0.035 Hz, whereas increasing the treadmill grade from -8% to +8% caused an increase in stride rate of 0.140 Hz. Similarly, Divert et al. (2008) found that the stride rate of runners significantly increased by 0.050 Hz with an addition of 350 g per foot. However, larger stride rate changes result from varied work rates. For instance, in Nordic skiing, Stöggl & Müller (2009) found cycle rate increased by 0.100 Hz while roller skiing at a grade of 8% compared to roller skiing at a grade of 2%. As a result, testing roller skiers at two different work rates will induce notable cycle rate changes and allow researchers to investigate the interaction between cycle rate and added mass on VO_2 .

This study will investigate the relationship between added mass on the limb with changes in economy (submaximal VO_2) and movement kinematics (cycle length and cycle rate) at two different work rates. Specifically, mass will be added to the ankle outside of the boots to simulate changes in equipment mass. While adding mass in this manner will not perfectly replicate the distribution of added mass throughout the ski/boot/binding system, this study will serve as an initial examination of the effect of changing equipment mass on economy and movement kinematics. For example, the placement of added mass on the outside of the boot might underestimate the true effect because additional mass from the ski has a greater radius from the hip axis and has an even greater effect on torque. Thus, differences in economy and movement kinematics observed in this study due to added mass could be even greater when the added mass is distributed throughout the equipment. The mass added to the boots in this study, however, should provide a necessary initial investigation into the effect of added mass on economy and movement kinematics of Nordic skate roller skiing.

Purpose

The primary purpose of this study was to identify the effects of added lower limb mass on economy during submaximal skate roller skiing. A secondary purpose was to determine the effects of added lower limb mass on movement kinematics during the same activity. The third purpose was to investigate whether the observed changes in economy and movement kinematics varied with work rate.

Hypotheses

The primary null hypothesis (H_0) was that no differences existed between the mean oxygen consumption (VO_2) values for the different limb-loading conditions. The alternative hypothesis (H_A) was that the mean VO_2 for at least one added mass condition was greater than the mean VO_2 for the control condition (i.e., no added mass).

$$H_0: \mu_{M0} = \mu_{Mx}$$

$$H_A: \mu_{M0} < \mu_{Mx}$$

where μ_{M0} represented the population mean for VO_2 while roller skiing at a standardized work rate with no additional mass, and μ_{Mx} represented population means for VO_2 while roller skiing at a standardized work rate with added mass (x) for at least one limb load condition.

The secondary null hypothesis (H_0) was that no differences existed between the mean movement kinematic (i.e., cycle rate) values for the different limb-loading conditions. The alternative hypothesis (H_A) was that the mean movement kinematics for at least one added mass condition was different from the mean movement kinematics for the control condition.

$$H_0: \mu_{M0} = \mu_{Mx}$$

$$H_A: \mu_{M0} \neq \mu_{Mx}$$

where μ_{M0} represented the population mean for cycle rate while roller skiing at a standardized work rate with no additional mass, and μ_{Mx} represented population means for cycle rate while roller skiing at a standardized work rate with added mass (x) for at least one limb load condition. A non-directional alternative hypothesis was used because

very little is known about the selection of a cycle rate by skate skiers. Therefore, if limb loading does affect cycle rate, it was unknown whether it would cause a decrease or an increase in cycle rate.

The third null hypothesis (H_0) was that work rate did not affect the observed changes in economy or movement kinematics. The alternative hypothesis (H_A) was that work rate affected at least one of the observed differences in economy or movement kinematics.

$$H_0: \mu_L = \mu_H$$

$$H_A: \mu_L \neq \mu_H$$

where μ_L and μ_H were the mean differences in economy or movement kinematics (i.e., cycle rate) at either a low (L) or high (H) work rate while roller skiing.

Delimitations

1. The study was delimited to 16-30 year old male and female cross country ski racers who were involved in pre-season training for the 2013-2014 racing season.
2. The study was delimited to submaximal treadmill skate roller skiing using the G3 technique.

Limitations

1. The sample was not random, but a convenience sample of volunteers from the local community.

2. This was not a blind study because subjects were aware of how much mass was added during each condition.

Assumptions

1. It was assumed that subjects were at steady state of exercise after 3 minutes at a submaximal work rate.
2. It was assumed that subjects followed the pre-testing instructions to abstain from exercise 24 hours prior to testing. Accordingly, subjects were assumed to be able to maintain the submaximal work rates without fatigue influencing measures of economy or movement kinematics.

Operational Definitions

Cycle length – A measure of the distance traveled per one repetition of a skate ski cadence. Cycle length was measured by dividing the treadmill speed by the cycle rate (Units of m/cycle).

Cycle rate – Cycle rate is a measure of the number of complete skate ski strides performed per unit of time. A complete G3 skate cycle, for example, consists of one right and one left leg push, each associated with a double pole plant (units of Hz).

Economy – According to Cavanagh & Kram (1985b), economy is the submaximal oxygen consumption per unit body mass required to perform a given task.

Energy expenditure – The rate of calorie utilization within tissues throughout the body, which can be estimated by measuring oxygen consumption during submaximal activities (Units of kcal/min).

G3 Technique – A symmetric cross country skate skiing motion where both poles are planted simultaneously, occurring just prior to each leg push when the body weight is shifted from one ski to the other. Also referred to as 1-skate or V2 technique.

Heart Rate (HR) – Heart rate is the rate of ventricular contractions which is often used as an indicator of aerobic exercise intensity (Units of beats/min, or bpm).

Lactate Threshold – The exercise intensity at which the rate of lactate appearance exceeds the rate of lactate disappearance in the blood. Intensities below lactate threshold are considered submaximal.

Oxygen consumption (VO_2) – The rate of oxygen used by the body to create energy from fuels during aerobic metabolism. When comparing different subjects, oxygen consumption values are often divided by body mass to produce a relative measure of oxygen consumption (Units of mL/kg/min).

Roller ski – A composite shaft of approximately 500 x 38 x 25mm (20 x 1.5 x 1”) with a wheel attached to each end and mounted with a skate skiing binding. Roller skis are used to imitate cross country skiing on smooth, non-snow surfaces.

Steady state – A condition where physiological measurements such as heart rate and oxygen consumption are stable during exercise at a constant submaximal work rate.

Submaximal intensity – Exercise at a work rate below that at which lactate accumulates in the blood (lactate threshold). Submaximal intensity is characterized by the use of aerobic metabolism exclusively to fulfill energy demands. As such, oxygen consumption is an accurate representation of total energy expenditure.

Work rate – The amount of power the roller skier must generate in the forward direction to stay on the treadmill, which is determined by the subject's mass, the rolling and friction resistances from the roller ski wheels, and the speed and grade of the treadmill (m/s and degrees). The total work rate is measured in Watts (W).

2. LITERATURE REVIEW

Introduction

Cross-country ski racers today ski at dramatically faster racing speeds compared to speeds seen in equal distance races in the past. In fact, Street (1992) specified that elite level ski races in the early 1900's took almost twice as long as an equal distance race today. Across all sports, performance has improved over the last century due to better training and nutrition practices. However, the improvements by Nordic skiers in the last 50 years are far greater than those observed in similar endurance sports. For example, over the last 65 years, the world record marathon running time has improved by 15%, from 2:25:39 in 1947 to 2:03:38 today (Marathon Records 2013). Meanwhile, comparable cross country ski races, such as a 30 kilometer classic, have seen race times drop by 41%, from approximately 125 minutes in 1950 (Street 1992) to just under 75 minutes in 2012 World Cup races (fis-ski.com 2013). Clearly, cross country ski race times have decreased to a greater extent than running race times, which indicates that Nordic ski racing has benefitted from advancements beyond those that have also affected running. Street (1992) believed the increased speed of Nordic skiing resulted from advancements in grooming and equipment technology. Specifically, the author theorized that the switch from wood to laminate skis, the change to modern pole materials, and the reduction in boot/ski/binding mass caused significant increases in race speed. Unfortunately, there is very little research that supports the conclusion that equipment was a factor in the improvement of race times.

Every successive generation of ski equipment is touted as being better than the previous generation and will improve skiing performance. Recently, every generation of skate skiing equipment has decreased mass, which the companies claim will enable racers to ski faster. As an example, the elite line of skate skiing equipment from Rossignol in 2010 was 210 g lighter per foot than the equivalent 2009 equipment (Rossignol Xium skis and boots; Cross-Country Skier Magazine 2010). Unfortunately, there are no published studies that have investigated the effects of Nordic ski equipment mass on performance, or markers of performance, so it is unknown whether this 210 g reduction in mass actually affects skiing performance. The proposed study would investigate the effects of added lower limb mass on economy and movement kinematics of roller skiing, both of which are considered markers of Nordic skiing performance.

Economy

In 1985(b), Cavanagh & Kram stated that an athlete's energy utilization is directly associated with endurance performance. The authors determined that the ability for one athlete to expend less energy while performing the same task as another athlete is an important attribute and can help explain performance differences. The authors noted that the measure of efficiency that is most applicable to performance is that of economy, which is the relative submaximal oxygen consumption required to perform a given task. As an example, when two subjects run at an equal absolute work rate, the runner with better economy has a lower relative VO_2 . Further, Mahood, Kenefick, Kertzer, & Quinn (2001) found that better economy while skate roller skiing correlated to better

performance in ski races. Therefore, roller skiing economy can be used as a marker of Nordic ski performance. Differences in economy often result from varied effectiveness of neuromuscular activation patterns; however, external factors, such as equipment characteristics, can also impact economy. Equipment mass is presumed to be one such factor in Nordic skiing, however, that has not been proven.

Load Carriage

In many situations, it is useful to know how energy expenditure is impacted by the addition of a load. When a load is added, more work must be performed to accelerate a greater mass, so it is expected that more energy is expended. This was confirmed when Taylor, Heglund, McMahon, & Looney (1980) found that mass added to animals increased their VO_2 in a directly proportional manner with the increase in total mass (body mass+load). Specifically, they identified a 1:1 ratio between percent increase in VO_2 with percent increase in total mass. In Nordic skiing, the observed differences in equipment mass are small relative to the total mass of the skier and equipment, so according to the findings by Taylor et al. (1980), the proportional increase in VO_2 is expected to be small. However, it is well-documented that placing mass on the limb, as is the case for ski equipment, produces a much larger effect than when the same mass is placed on the torso (Marsh, Ellerby, Carr, Henry, & Buchanan 2004; Myers & Steudel 1985). Specifically, Myers & Steudel (1985) found increases in VO_2 were 1.5 and 5.5 times larger when mass was added to the thigh or ankle, respectively, than when the same mass was added to the torso. The authors proposed that the placement of the mass was

important because of its impact on the limb's moment of inertia. The moment of inertia is a property of an object that defines how much torque is required to accelerate the object about an axis. The moment of inertia exponentially grows as the radius from the axis increases. Thus, as mass is placed more distally on a limb, the torque required to accelerate the limb increases exponentially. For the muscles to generate greater torque about the hip joint, they must apply more force, which increases energy expenditure, as was observed by Myers & Steudel (1985). Clearly, accelerating the limbs can be energetically expensive. In fact, Myers and Steudel (1985) calculated that simply changing the kinetic energy of the lower limbs accounted for approximately 30% of the total energy expended by their subjects while running. By extending these calculations, they noted that at higher speeds of running, the portion of energy devoted solely to kinetic energy changes would notably increase.

While Myers & Steudel (1985) only used theoretical calculations, Marsh et al. (2004) collected data that validated the theory. Marsh et al. (2004) used blood flow tracking to determine the proportion of energy required by each of the muscles that were active while running. The authors observed that 74% of the energy used by the lower limbs in a running stride was used by stance-phase muscles, and the remaining 26% was used by swing-phase muscles. Swing phase muscles are solely used to accelerate the limb, with no propulsion of the body, so it is impressive that they consume more than a quarter of the energy required for running. The high cost of simply swinging the limbs reflects the torque requirements to accelerate the leg about the hip and knee joints. An increase in torque requirements, as with additional mass on the foot, will cause an

increase in the proportion of energy devoted to swinging the limbs. Many researchers have agreed and found that even an addition of a small limb load to the feet of runners causes a significant increase in economy (Divert et al 2008; Franz et al. 2012; Martin 1984). Even though skate skiing has a different motion pattern than running, the limbs are similarly accelerated, including a propulsive stance phase and a swing phase, and there are similar energetic and neural demands (Stöggl & Müller 2009). As a result, it is likely that the effect of added mass on the lower limbs in skate skiing is similar to that of running.

Kinematics

A kinematic analysis of motion involves describing the position of a body in space and how it changes over a period of time without regard to the forces required to create the motion. Important information can be gained from kinematic analyses, such as the rate of movement of body segments or the range of motion of a joint. These and other descriptive factors can be used to identify differences between amateur and elite athletes, the discovery of which can guide the training of young athletes as they strive to improve (Kinematics 2008). Within a cyclic activity such as Nordic skiing, two movement kinematic variables interact to determine skiing velocity: 1) the distance travelled per skate stride (cycle length) and 2) the frequency of strides taken (cycle rate). If either cycle rate or cycle length changes while the other remains constant, the skier's velocity will change. Interestingly, several studies have shown that skiers tend to increase their speed by increasing their cycle rates (Andersson et al. 2008; Millet et al.

1998; Stöggl & Müller 2009). In contrast, when skiers of varied skill levels are compared on similar terrain, faster skiers use longer cycle lengths with similar cycle rates (Bilodeau et al. 1996; Rundell & McCarthy 1996; Sandbakk et al. 2011). As a result, both cycle rate and cycle length are important components in the ability to ski quickly, and a decrease in either factor could negatively impact racing performance.

It is well documented that there is a relationship between the amount of force a muscle generates and the velocity at which it is able to contract (Rahikainen, Avela, & Virmavirta 2012). Specifically, as the force requirements of a contraction increase, the maximal velocity of that muscle contraction decreases, which is a relationship defined as the force-velocity curve. In cross-country skiing, propulsive forces are generated quickly, followed by a recovery period (Stöggl & Müller 2009). Because of its distal placement, ski equipment exponentially increases the moment of inertia of the lower limb. If skiers have heavier equipment, the force required to accelerate the leg is substantially greater, which, according to the force-velocity curve, will slow the speed of contraction. To compensate, the skier are likely to reduce their overall cycle rate. Unfortunately, a lower cycle rate has been suggested to result in slower overall speed, which decreases performance in races (Andersson et al. 2008; Millet et al. 1998; Stöggl & Müller 2009). While the phenomenon of decreased cycle rate with increased equipment mass of skate ski equipment has not been documented, several researchers have found significant differences in running stride due to shoe mass. In multiple studies, heavier shoes have been found to decrease stride rate in running (Divert et al. 2008; Lussiana, Fabre, Hebert-Losier, & Mourot 2013). On average, Lussiana et al. (2013)

found that when subjects ran in minimalist shoes, their stride rates were approximately 0.035 Hz higher (1.3% increase) than when they ran in traditional shoes that were 146 g heavier per foot. The authors noted that foot strike patterns were different between the shoe types and might have contributed to the different stride rates observed. However, Divert et al. (2008) made similar findings without a change in type of footwear. Specifically, the researchers added weights to running socks so that the mass of a traditional running shoe could be investigated without changing the other characteristics of the footwear. In doing so, they found that the stride rate of runners varied by 0.050 Hz with an addition of 350 g per foot. Since mass added to the lower extremity affects movement kinematics in running, it is possible that a similar phenomenon occurs in Nordic skiing, but no published studies have investigated the effect of limb loading on Nordic skiing movement kinematics.

The Effect of Equipment Mass on Oxygen Consumption

There are no currently published studies available that have investigated the effect of limb-loading in Nordic skiing. In contrast, the effect of added mass to running and hiking shoes is well-studied. Despite the fact that running involves a different movement pattern than skate skiing, Stöggel & Müller (2009) noted that running has similar neuromuscular and aerobic demands to Nordic skiing. Thus, added mass to the lower limb will likely have similar effects on both forms of locomotion.

The energetic impact of added mass on the feet was first studied in the 1940's, when the US Army hired Russell & Belding (1946) to investigate the energetic difference

between walking barefoot and walking wearing combat boots. For every kilometer the subjects walked, it was found that oxygen consumption increased by 0.25 liters/kg while walking in the combat boots compared to barefoot (910 g difference per foot). In 1969, two research groups drew similar conclusions in their research on hiking boots.

Specifically, Soule & Goldman (1969) researched the impact of adding 6 kg to each foot of hikers at three different speeds. They found not only that there was a significant increase in oxygen consumption when the feet were loaded, but that there was a non-significant trend of greater increase at higher speeds. While walking at 4, 4.8, and 5.6 km/hr, the added mass caused absolute VO_2 to increase by 70%, 95%, and 103% above the unloaded condition, respectively. At the same time, Ralston & Lukin (1969) found that energy expenditure of hiking increased by 30.9% with an addition of a 2 kg mass on each foot. Clearly, the mass of boots has an impact on the energy required for hiking.

After several studies confirmed the effects of mass on hiking, many researchers investigated the effect of the shoe mass on running energetics. For example, Jones, Toner, Daniels, & Knapik (1984) studied the effect of hiking and running in athletic shoes compared to leather boots in both trained and untrained individuals. The subjects performed trials at three different walking speeds and three different running speeds, and the running speeds were repeated using mass added to the athletic shoes such that the mass was equal to the heavy boots. They found significant differences in energy expenditure for both walking and running, regardless of training status. Oxygen consumption per 100 g additional mass on each foot increased by an average of 1.2%, 1.5%, and 0.9% for walking, running in boots, and running in athletic shoes with added

mass, respectively. Similarly, Martin (1984) reported 3% and 7% increases in VO_2 when runners were loaded with 250 g and 500 g per foot, respectively.

Recently, researchers have investigated the economy differences between running in shoes and running barefoot. The conclusions from the early studies suggest that running barefoot should result in better economy because there is less mass on the feet, but Divert et al. (2008) noted that several of the studies compared two different models of footwear, which added an uncontrolled variable. They believed that the characteristics of the shoe, such as different amounts of cushioning, might have altered the runners' kinematics and confounded the results. As a result, Divert et al. (2008) attempted to investigate the effects of mass without a change in shoe properties. They did so by having the subjects run in socks that resembled barefoot running, and then they added weights to the socks to resemble the extra mass of running shoes. By comparing running in socks without extra mass to running in socks with added mass, the researchers found that VO_2 increased by about 1.2% per 100 g of mass added to each foot. Later, Franz, Wierzbinski, & Kram (2012) commented that foot-strike type was not documented in the study by Divert et al. (2008). Franz et al. (2012) theorized that the subjects might have used different foot-strike patterns, which could have impacted the results. Franz et al. (2012) performed a follow-up study that controlled for strike type. The researchers confirmed the results of Divert et al. (2008) by finding a 0.9% increase in VO_2 per 100 g increase in mass on each foot.

Decades of research has confirmed that adding mass to the lower extremity significantly changes oxygen consumption. When these studies are standardized to an

addition of 100 g per foot, they conclude that VO_2 will increase by 0.9-1.5%, which is summarized in Table 2.1.

Table 2.1. Effect of added mass on running and walking studies. Percent differences in oxygen consumption (VO_2) from the control condition have been standardized to the observed increase per 100 grams per foot.

Date	Authors	Run/Walk	Mass Added per Foot	VO_2 Diff per 100 g per Foot (%)
1969	Ralston & Lukin	Walk	2.00 kg	1.54
1969	Soule & Goldman	Walk	6.00 kg	1.49
1984	Jones et al.	Both	0.58 kg	1.26
1984	Martin	Run	0.25 & 0.50 kg	1.38
2008	Divert et al.	Run	0.10 & 0.30 kg	1.24
2012	Franz et al.	Run	0.15, 0.30, & 0.45 kg	0.91

When mass is added to a running shoe, it is directly attached to the foot and swings exactly as the foot does. This is not necessarily the case in Nordic ski equipment, where skis extend beyond the feet. As a result, the effects of additional mass distributed throughout a ski might be different than those of a running shoe. While there are no published studies that investigate the effect of the mass of skis on economy, researchers have investigated the effect of using hiking poles on economy of hiking. The use of poles is similar to skis in that they extend beyond the extremity and the swing pattern does not directly follow that of the hand. Walking with hiking poles has been found to increase VO_2 by 12% and 23% when the poles are 340 g and 450 g each, respectively (Hendrickson et al. 1997; Rodgers, VanHeest, & Schachster 1995). These findings equate to 3.5% and 5.1% increases in VO_2 per 100 grams added to each hand. Interestingly, neither study included poles of different masses, so the only comparison

was between walking without poles to walking with poles. Because the addition of poles changes the kinematics of walking, it is likely that the altered movement patterns contributed to the change in VO_2 . However, the increased mass at the distal point of the upper extremity was presumed to be the primary cause of the increased energy expenditure. Similar to the addition of mass to a running shoe, the hiking poles needed to be accelerated with every stride, which increased the energy demands of the extremity. The same increase theoretically occurs when the mass of Nordic skis, boots, and bindings increase, but the exact relationship is unknown.

Clearly, adding mass to the extremity can influence the economy of movement, but the precise amount of lower limb loading required to significantly affect skate skiing has not been investigated. In one review article by Street (1992), it was proposed that for every reduction of 100 g per foot for the ski/boot/binding system, a ski racer will reduce race time by 0.8%. Unfortunately, no study is referenced to validate the statement, so the effect of lower limb loading on skate skiing economy remains unknown.

Cycle Rate Variation

It is expected that lower limb loading during skate skiing will increase energy expenditure because the added mass will affect the torque requirements to swing the legs. Swinging the limbs is energetically expensive even without limb loading and will increase dramatically when loaded. Further, Myers & Steudel (1985) commented that the proportion of energy devoted to swinging the legs during running substantially increases with faster running speeds. When the energy devoted to leg swing increases, the effect of

mass on the distal portion of the limb might be exaggerated. For instance, a higher cycle rate might result in greater changes in economy with the same amount of limb loading. Interestingly, in running and walking studies, the relationship between added limb mass and economy has consistently been found to be approximately 1% for every 100 g addition to the leg, regardless of stride rate or running speed (Divert et al. 2008; Franz et al. 2012; & Jones et al. 1984). However, none of these studies have specifically investigated whether stride rate interacts with added mass. An intentional manipulation of cycle rate would be useful to investigate whether an increased cycle rate affects the observed changes in economy or kinematics from limb-loading.

Treadmill Speed and Grade to Manipulate Kinematics

In Nordic skiing, velocity is determined by a combination of the cycle rate and cycle length used (Sandbakk et al. 2012a). When athletes are allowed to freely choose their own cadence, they tend to pick a cadence close to that which optimizes their economy of motion (Cavanagh & Williams 1982). For skate roller skiing, Reinking (2013) determined that sub-elite level skiers chose a cadence solely based on the total external power demand, rather than selecting a cycle rate based on either the speed or the grade alone. This indicates that the manipulation of cycle rate requires variation of the total external power demand. As such, this study will use two work rates that vary in external power demand in order to investigate the possible interaction between cycle rate and added mass on economy.

In the proposed study, subjects will use the G3 technique, which is typically selected by skiers while skiing at moderate speeds over flat or gradual uphill terrain (Sandbakk et al. 2012). When the G3 technique is used in other circumstances, skate skiing efficiency decreases. For example, Kvamme et al. (2009) recently observed that the G3 technique is an efficient skate skiing technique for sub-elite competitive male skiers for grades of up to 5° . At steeper inclines, the subjects were still able to perform the G3 technique, but their efficiency decreased. Further, Sandbakk et al. (2012a) found that elite level skiers were more efficient using the G3 technique at an 8% grade (4.5°) than a 2% grade (1.1°), indicating that the use of the G3 technique at low gradients is also inefficient. Clearly, the G3 technique is optimized at moderate uphill grades. Because subjects should be roller skiing as efficiently as possible, the work rates selected for this study included grades of 2° and 3.15° .

Conclusion

Using running shoe research as a model, it has been argued that the decreased mass of Nordic ski equipment has contributed to the improvement in Nordic skiing performances over recent decades. Similarly, it is possible that the differences in the mass of equipment between successive generations, as well as between current models of equipment, affect skiing performance. However, no research has been published that would support these claims. A study to investigate the effects of limb loading on the economy and movement kinematics of skate roller skiing is necessary to better understand how variations in equipment mass impact Nordic skiing.

CHAPTER THREE

THE EFFECT OF LOWER LIMB LOADING ON ECONOMY AND KINEMATICS
OF SKATE ROLLER SKIING

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

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Contributions: Assisted with study design, implemented data collection, processed and analyzed data, and wrote manuscript.

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Contributions: Conceived the study design, assisted with data processing and analysis, discussed results and implications, and was primary editor of the manuscript at all stages.

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Abstract

It has been proposed that skate skiing economy and racing performance have improved as a result of lighter equipment. Despite the many studies that have found running and walking economy to improve with lighter shoes, there are no published studies that show any relationship between the mass of skate skiing equipment and markers of skate skiing performance. To investigate the effects of skate skiing equipment mass on markers of performance, this study added mass to the lower limbs of skate roller skiers and measured changes in economy and gross movement kinematics. Twelve male (Mean±SD; Age (yrs): 21.4±3.9) and eight female (Mean±SD; Age (yrs): 19.9±2.2) competitive cross-country skiers completed two laboratory visits to roller ski on an oversized treadmill. In the first visit, subjects completed a graded exercise test to determine their lactate threshold. In the second visit, subjects completed 5 minutes of roller skiing at a low work rate (2 m/s for women and 3 m/s for men both at 2⁰) and a high work rate (2 m/s for women and 3 m/s for men both at 3.15⁰) for each of the four limb loading conditions (0 g, 200 g, 400 g, and 600 g). Oxygen consumption (VO₂), heart rate (HR), and cycle rate were measured during the last 2 minutes of each stage and used for analysis. There were no significant differences in HR, VO₂, or cycle rate between any of the limb loading conditions at either work rate. However, cycle rate neared significance (P = 0.06), with increases in cycle rate observed during greater limb loading. Interestingly, VO₂ and HR significantly increased throughout testing, independent of limb loading condition. The most notable increases were observed in HR values, and increases began within the very first testing stage. Thus, it is likely that the

subjects experienced cardiovascular drift due to mild hyperthermia. The cardiovascular drift might have masked the true effects of lower limb loading. Therefore, future studies still need to investigate the effects of lower limb loading on skate skiing economy and kinematics.

Introduction

Cross country skiing is typically considered to be an aerobic sport. As such, there has been considerable focus on skiers' capacities for maximal oxygen consumption (VO_{2max}). In fact, it is well documented that VO_{2max} is a strong predictor of cross country ski performance among heterogeneous populations (Hoffman & Clifford, 1992; Losnegard, et al., 2012a; Sandbakk et al., 2010). Unfortunately, within homogeneous populations, the correlation between VO_{2max} and performance significantly weakens and other variables have been found to better predict performance. Among the other variables that correlate with cross country skiing performance are upper body power (Alsobrook & Heil 2009; Staib et al. 2000), treadmill velocity at lactate threshold (Stöggl et al. 2007; Vesterinen et al. 2009), accumulated oxygen deficit during a time trial (Losnegard et al. 2012a; Reinking et al. 2012), and skate roller skiing economy (Mahood et al. 2001). Athletes can use this research to learn which characteristics are most important to performance, which can then become the focus of their training. The knowledge gained from research allows athletes in all sports to improve their performance capabilities, as can be demonstrated in individual sports by progressively decreasing race times.

Throughout the last several decades, improvements in training and nutrition practices have led to faster race times in many endurance based sports. For example, the winning time in the 10 km run at the 2012 Olympics was 1.0% faster than the same event at the 1984 Olympics (27:30.42 in 2012, 27:47.54 in 1984; Olympic.org 2013).

Interestingly, the improvements in cross country skiing over the same time frame have been dramatically greater. For example, the winning time in a World Cup 10 km skate ski race in 2012 was 27.4% less than the winning time of the 10 km skate ski race in the 1985 World Championships (31.0 minutes in 1985 to 22.5 minutes in 2012; fis-ski.com 2013). Clearly, there have been improvements in cross country skiing that have not been observed for other endurance sports, such as running, over the same time frame.

It has been proposed that improvements in grooming, more advanced ski wax and ski structure, and lighter equipment have enabled better skiing economy and, therefore, faster ski racing speed (Street 1992). Within the external factors affecting economy, Street (1992) stated that the largest contributor to improvements in ski racing performance was the reduction in the mass of ski equipment. Specifically, the author proposed that a skier's race time would decrease by 0.8% for every 100 g reduction in the combined mass of the ski, boot, and binding on each leg. Unfortunately, no published data exists that identifies the effect of reduced mass on the lower limb on skate skiing economy.

Although no research exists specific to skate skiing, many studies have investigated the effect of lower limb loading on walking and running economy. These studies have consistently found that VO_2 while hiking or running increases by around 1%

for each additional 100 g per foot (Divert et al. 2008; Franz et al. 2012; Jones et al. 1984; Martin 1984; Ralston & Lukin 1969; Soule & Goldman 1969). Therefore, if skate skiers respond to decreased limb loading in a similar manner as that of runners, then a decreased lower limb load would improve skiing economy and possibly improve skiing performance.

A study investigating the effect of lower limb loading on skate skiing economy would help assess whether the improvements in skate ski race times between 1980 and 1992 resulted from changes in equipment mass, as Street (1992) proposed. Also, a study would help identify the importance of more recent changes in skate skiing equipment, as significant advancements in equipment have been made since Street's article was published in 1992. Notably, ski equipment released each year continues to become lighter than the previous commercially available equipment. For example, in 2010-2011, several companies advertised mass reductions of between 150-200 g for a pair of elite-level skis, boots, or bindings compared to the best available pair of skis, boots, or bindings from the previous year (Cross-Country Skier Magazine 2010). Further, the masses of skate ski packages available within each generation of equipment can vary dramatically. In fact, in 2013, two skate ski packages could differ by as much as 740 g. When a skier upgrades from an old sub-elite equipment package to a new elite equipment package, even greater decreases in mass could be observed. However, it is unknown whether a 740 g reduction in equipment mass affects skate skiing economy or performance. Therefore, this study added mass to the lower limbs of skate roller skiers (0 g, 200 g, 400 g, and 600 g per foot) to simulate skiing with heavier equipment and

identify the effects of lower limb loading on markers of skate skiing performance. Skate roller skiing economy and gross movement kinematics were used as markers of skate skiing performance. The purpose of this study was to test the hypothesis that oxygen consumption and cycle rate are affected by the addition of mass on the lower limb. Specifically, it was expected that increased lower limb loading would increase oxygen consumption.

Methods

Study Design

During this study, mass was added to subjects' lower limbs to investigate the effect of limb loading while treadmill skate roller skiing on measures of oxygen consumption (VO_2), heart rate (HR), and cycle rate. This was a repeated measures study with a crossover design. Test order for the four limb loading conditions (0 g, 200 g, 400 g, and 600 g per foot) was counterbalanced between the subjects and across a pre-determined sequence of two treadmill work rates. These mass conditions were chosen because pilot testing indicated that differences in energy cost begin to appear with ≥ 500 g per foot. Additionally, similar mass differences can be observed between commercially available skate ski equipment packages.

Subjects

Twenty 16-29 year old male and female cross-country skiers from the Montana State University and Bridger Ski Foundation ski teams, all of whom were actively training for the current competitive ski season, were recruited to participate in this study.

The subjects were informed of the research protocol prior to participating and signed an informed consent form approved by the Montana State University Institutional Review Board. Parental consent was obtained for all subjects under 18 years of age. Subjects also completed a physical activity readiness questionnaire for health screening prior to exercise testing.

Testing Procedures

All subjects performed two testing sessions. During the first visit, subjects were familiarized to roller skiing on the treadmill and performed a lactate threshold (LT) test. The second visit entailed roller skiing on the treadmill under each of the four limb loading conditions (0 g, 200 g, 400 g, or 600 g attached to each foot) to simulate heavier ski equipment. The subjects performed each limb loading condition at two standardized work rates (3 m/s at 2° and 3.15° for men and 2 m/s at 2° and 3.15° for women). Subjects utilized the G3 skating technique throughout all test stages. Subjects were requested to abstain from high volume or high intensity exercise within 24 hours prior to each test session to minimize the effects of fatigue.

Upon arriving at the lab for the first visit, each skier, while wearing only exercise clothing and no ski boots, was measured for both body height (cm) and mass (kg) (Health-O-Meter beam scale, Continental Scale Corp., Bridgeview, IL, USA) using standard procedures. Then, the subject roller skied on the treadmill at a freely chosen work rate for 10 minutes to warm up. Next, the subject began a graded exercise test. Each stage lasted 4 minutes during which 3 minutes of roller skiing was followed by 1 minute of rest before progressing to the next stage. During the one-minute rest, a

fingertip blood sample was collected and then measured for blood lactate concentration using a handheld analyzer. The LT protocol was stopped when a blood lactate measure both exceeded 4.0 mmol/L and exceeded the previous blood lactate measure by ≥ 1.0 mmol/L. Once this occurred, the subject began 5 minutes of active recovery while roller skiing at 2° and 1.8 m/s (4 mph). The results from each subject's lactate threshold test were processed prior to their second visit to the laboratory. This allowed the researchers to ensure that all subjects were roller skiing at a submaximal intensity during visit 2.

The second visit also began with the measurement of body weight prior to 10 minutes of roller skiing on the treadmill to warm-up. The warm-up for the second visit consisted of 5 minutes of roller skiing at a freely chosen work rate followed by 5 minutes of roller skiing at the lower standardized work rate that would be used during testing. The subject then had 5 minutes of rest while the researcher set up the portable metabolic system and added mass for the first limb load condition. The limb load was applied by securing 100 g mass discs to the plastic cuff of the ski boot at the lateral malleolus using athletic tape. Once all equipment was in place, the subject completed stage 1 by roller skiing for 5 minutes at the first test condition and work rate, which was followed immediately by another 5 minutes of roller skiing at the same limb load condition and the second work rate. Upon completion of the first two stages, the subject had 5 minutes to rest while the mass condition was changed. The same procedures were then repeated for the remaining three limb loading conditions. Test order for mass conditions was counterbalanced between the subjects and across a pre-set sequence of work rates. After every two stages, the amount of mass on the boots was changed, and the subject was

allowed to rest for 5 minutes. Once all eight stages were completed, the subject roller skied for 5 minutes to cool down on the treadmill at a freely chosen work rate.

Work Rate Selection

During visit 2, each skier roller skied at standardized low (L) and high (H) work rates. All male subjects roller skied at 3 m/s at a grade of 2° (L) and 3.15° (H), while all female subjects roller skied at 2 m/s at 2° (L) and 3.15° (H). These work rates were based upon previous testing of skiers with similar fitness and skill, and were found to be submaximal for all subjects (Reinking 2013). Also, the grades were chosen because the G3 technique has been shown to be optimal while roller skiing between 1.5° and 4° (Kvamme et al. 2009; Sandbakk et al. 2012a).

Justification for Limb-Loading Conditions

Pilot testing with a single subject indicated no meaningful changes in VO_2 while skate roller skiing with 200 or 300 g added per foot when compared to the control condition. A 1% increase in VO_2 required the addition of 500 g added per foot. Further, mass differences of up to 600 g are relevant when compared to recent changes in total ski/boot/binding equipment mass. For example, two equipment packages from the most recent generation can differ by up to 370 g per foot. Thus, an upgrade from a previous generation of sub-elite equipment to new elite equipment would likely include a larger reduction in total equipment mass.

Instrumentation

Roller Skiing Equipment. All testing was performed in Montana State University's Movement Science Lab on an oversized treadmill (2.5 meters wide, 3 meters long; Fitnex Fitness Equipment Inc., Dallas, TX) using Marwe 610 skate roller skis (Hyvinkaa, Finland) with either SNS (Salomon, Annecy, France) or NNN (Rottefella, Klokkearstua, Norway) bindings. Subjects also used either Swix CT1 (Swix, Lillehammer, Norway) or Madshus Carbon Race 70 (Madshus, Biri, Norway) poles selected to the nearest 2.5 cm increment of preferred length. Both models of poles are similar, high-level racing poles, and the subject used the same pair for both visits. Subjects completed all testing using their own skate ski boots. Video was recorded during the last two minutes of each stage during visit 2 and used for analysis of gross movement kinematics (Logitech Pro C920 webcam; Logitech, Silicon Valley, CA, USA).

Indirect Calorimetry. Oxygen consumption was measured and recorded with a portable metabolic system (Oxycon Mobile, Viasys Healthcare, Yorba Linda, CA) using standard indirect calorimetry procedures. The metabolic system was calibrated according to manufacturer's guidelines before the start of each test. Polar RS400 heart rate monitor chest straps (Polar Electro, Inc., Lake Success, NY) were used to measure HR, which was remotely transmitted to and recorded by the Oxycon metabolic system.

Lactate Testing. During lactate threshold testing, a whole-blood sample was taken from the fingertip using a single-use lancet. Blood lactate concentrations were

measured using a Lactate Pro analyzer (Lactate Pro; Arkray, Inc., Kyoto, Japan).

Calibration of the Lactate Pro analyzer was performed prior to each testing session according to the manufacturer's guidelines.

Data Processing

The metabolic system measured breath-by-breath data and then summarized these data as 5 second averages. Steady-state values for VO_2 and HR were taken as an average over the final 2 minutes of each stage. Threshold values of HR and VO_2 were determined by averaging the steady state values from the last two stages of the first visit.

The video from visit 2 was used to manually record the time taken to complete 10 skate cycles. The skate cycle both started and finished with a double-pole plant associated with a left leg push. Cycle rate (in Hz) was then calculated by dividing 10 by the time (in seconds) to complete 10 cycles.

Statistical Analysis

A multivariate repeated measures two-way analysis of variance (ANOVA) was performed with added mass (4 levels) and work rate (2 levels) serving as the main effects tested. Post-hoc comparisons were performed with Tukey's multiple comparisons tests. All tests were performed at the 0.05 alpha level.

After the primary analysis was performed, it was decided that a sub-analysis was necessary to test for significant differences between test stages, independent of the limb loading condition. For the sub-analysis, an ANOVA test was performed to compare the four test stages at each work rate. As with the primary analysis, post-hoc comparisons

were made using Tukey's multiple comparisons test, and all tests were performed at the 0.05 alpha level.

To test the assumption that subjects were at a steady-state during the last 2 minutes of each stage, the physiological variables were assessed for reliability between the fourth and fifth minutes. Each stage of the test sequence was evaluated with high and low work rates analyzed separately. Reliability was analyzed with an ANOVA as well as by observing the intraclass correlation coefficients (ICC) and the standard error of measurements (SEM) for each variable.

Pilot Testing

In May, 2013, a subject roller skied for 4 minutes at a set work rate (2.9 m/s at 3.4⁰) using four different limb loading conditions (0 g, 200 g, 300 g, and 500 g per foot). Oxygen consumption (VO₂) and heart rate (HR) values were recorded throughout the testing. Values from the last minute of each stage were considered steady-state and averaged for analysis. The results from this test are summarized in Table 3.1.

Table 3.1. Mean oxygen consumption (VO₂) and heart rate (HR) for a subject with four different limb loads during a pilot test. The percent difference in VO₂ from the control condition is also listed.

Stage	Mass Added (g per foot)	Average VO₂ (mL/kg/min)	Average HR (bpm)	Difference in VO₂ from Control (%)
1	0	45.45	147.0	--
2	200	45.78	148.3	0.72
3	300	45.98	146.3	1.16
4	500	47.25	146.0	3.96

Results

Subjects

Twenty subjects (8 female, 12 male) were recruited to participate in this study.

The subject's demographics for each gender are presented in Table 3.2.

Table 3.2. Subject Demographics (Mean±SD)

Gender	N	Age (years)	Body Height (cm)	Body Mass (kg)	VO ₂ at LT (ml/kg/min)	HR at LT (bpm)
Male	12	21.4 ± 3.9	182.1 ± 8.25	77.2 ± 11.0	51.1 ± 6.2	172.3 ± 7.8
Female	8	19.9 ± 2.2	165.9 ± 6.5	60.6 ± 4.7	44.5 ± 3.1	187.8 ± 11.6

Physiological Variables

There were no significant differences for any of the physiological variables between the four limb loading conditions at either work rate ($p = 0.24 - 0.83$). Mean VO₂ and HR values observed during each limb loading condition are displayed in Figure 3.1. Further, only ventilation rate (V_e) showed a significant interaction between the limb loading condition and the work rate ($p = 0.03$), while all other variables showed no significant interactions ($p = 0.21 - 0.72$). There was a slight tendency that mean VO₂ increased with greater limb loading ($R^2 = 0.72$ and 0.74 for the high and low work rates, respectively). However, there was a very low correlation between the limb loading condition and mean heart rate ($R^2 = 0.70$ and 0.01 for high and low WR, respectively).

Interestingly, during testing, it was observed that there was a possibility of an order effect. As a result, an ANOVA was performed comparing test stages regardless of limb loading condition. The ANOVA found significant differences for all physiological

variables due to test sequence ($p \leq 0.001$). As the test progressed, all physiological variables consistently increased, except RER, which decreased throughout testing. This data is summarized in Table 3.4. Testing sequence had strong positive correlations with mean VO_2 and HR values ($R^2 = 0.88 - 0.92$).

Table 3.3. Physiological values (Mean \pm SE) observed at each limb load condition for both low (L) and high (H) work rates.

Condition (Work Rate)	VO_2	HR	RER	Ve	Bf
000 g (L)	31.5 ± 1.2	144.6 ± 2.6	0.86 ± 0.01	62.3 ± 4.2	36.3 ± 1.5
200 g (L)	31.5 ± 1.3	146.5 ± 2.5	0.86 ± 0.01	62.8 ± 4.6	36.6 ± 1.7
400 g (L)	31.6 ± 1.2	146.1 ± 2.8	0.86 ± 0.01	62.6 ± 4.3	35.5 ± 1.6
600 g (L)	32.1 ± 1.2	147.2 ± 2.9	0.86 ± 0.01	63.8 ± 4.4	37.0 ± 1.7
000 g (H)	41.4 ± 1.6	162.8 ± 2.7	0.90 ± 0.01	84.6 ± 6.5	39.5 ± 1.3
200 g (H)	41.2 ± 1.8	164.1 ± 2.7	0.90 ± 0.01	84.5 ± 6.7	39.4 ± 1.5
400 g (H)	41.7 ± 1.7	163.7 ± 2.8	0.91 ± 0.01	86.0 ± 6.6	40.1 ± 1.6
600 g (H)	41.9 ± 1.7	164.4 ± 2.8	0.91 ± 0.01	86.6 ± 6.6	40.3 ± 1.6

Table 3.4. Physiological variables by testing sequence and work rate (Mean \pm SE).

Stage (WR)	VO_2 (ml/kg/min)	HR (bpm)	RER	Ve (l/min)	Bf (min^{-1})
1 (L)	30.8 ± 1.6	141.0 ± 3.6	0.89 ± 0.01	61.2 ± 5.8	33.9 ± 2.0
2 (L)	31.5 ± 1.7	$146.2 \pm 3.7^*$	$0.87 \pm 0.01^*$	62.8 ± 6.1	$36.1 \pm 2.2^*$
3 (L)	$32.2 \pm 1.8^*$	$148.1 \pm 3.8^*$	$0.85 \pm 0.01^{*\dagger}$	$63.7 \pm 6.5^*$	$37.3 \pm 2.4^*$
4 (L)	$32.3 \pm 1.8^{*\dagger}$	$149.1 \pm 3.8^{*\dagger}$	$0.84 \pm 0.01^{*\dagger}$	$63.9 \pm 6.4^*$	$38.1 \pm 2.3^{*\dagger}$
1 (H)	40.4 ± 2.4	159.2 ± 3.6	0.92 ± 0.02	82.4 ± 8.8	37.5 ± 1.9
2 (H)	$41.5 \pm 2.3^*$	$163.6 \pm 3.7^*$	$0.91 \pm 0.02^*$	$85.5 \pm 9.5^*$	$39.3 \pm 2.1^*$
3 (H)	$42.1 \pm 2.5^*$	$165.6 \pm 4.0^*$	$0.89 \pm 0.01^{*\dagger}$	$86.7 \pm 9.5^*$	$41.0 \pm 2.0^{*\dagger}$
4 (H)	$42.2 \pm 2.4^*$	$166.5 \pm 3.8^{*\dagger}$	$0.89 \pm 0.01^{*\dagger}$	$87.2 \pm 9.4^*$	$41.5 \pm 2.3^{*\dagger}$

Note: All values at the low work rate were statistically different from all values at the high work rate. * Statistically different ($p < 0.05$) from stage 1; † Statistically different ($p < 0.05$) from stage 2.

Reliability Analysis

A repeated measures ANOVA found that mean HR was statistically different ($p \leq 0.05$) between the fourth and fifth minutes for 9 of the 16 test stages. Meanwhile, VO_2

values were not significantly different ($p = 0.06 - 0.92$) between the fourth and fifth minute for any stage. The remaining physiological variables (RER, V_e , and Bf) had 1-3 stages where the last two minutes were significantly different ($p < 0.05$). Mean values for the fourth minute at all other stages were statistically similar to mean values from the fifth minute ($p = 0.06 - 0.94$). The results of the ANOVA are shown in Table 3.5.

Table 3.5. ANOVA p-values comparing the mean values for physiological variables during the fourth minute with the same values from the fifth minute at each test stage. Note that each skier performed only one of the work rates for each stage (i.e., either 1 (L) or 1 (H) but not both) for a total of 8 of the 16 stages.

Stage (WR)	VO ₂	HR	RER	Ve	Bf
1 (L)	0.27	0.09	<0.01*	0.02*	0.33
1 (H)	0.28	0.02*	0.58	0.28	0.26
2 (L)	0.20	0.64	0.31	0.15	0.60
2 (H)	0.10	0.06	0.15	0.29	0.10
3 (L)	0.26	0.01*	0.04*	0.06	0.42
3 (H)	0.35	0.01*	0.27	0.30	0.31
4 (L)	0.60	0.01*	0.28	0.86	0.87
4 (H)	0.24	0.65	0.75	0.50	0.40
5 (L)	0.26	<0.01*	0.69	0.09	0.02*
5 (H)	0.92	0.02*	0.08	0.50	0.54
6 (L)	0.68	0.30	0.16	0.55	0.22
6 (H)	0.06	0.01*	0.93	0.03*	0.19
7 (L)	0.26	0.41	0.01*	0.18	0.24
7 (H)	0.49	0.01*	0.79	0.51	0.49
8 (L)	0.74	0.51	0.94	0.35	0.18
8 (H)	0.59	0.05*	0.57	0.76	0.69

*Significant difference ($p \leq 0.05$) between minutes 4 and 5.

In contrast to the results of the ANOVA, each physiological variable analyzed had high ICC (0.79 – 1.00) and low SEM (0.00 – 4.21) values at every stage. The high ICC and low SEM values resulted from the high variability between subjects, and therefore were less useful for identifying trends within subjects. As a result, the reliability analysis as a whole indicated that HR tended to drift and could not be considered steady-state,

whereas the other variables were fairly consistent within each stage and could be considered steady-state values.

Cycle Rate

Cycle rate was significantly different between work rates ($p < 0.01$) for all limb load conditions. Interestingly, cycle rate was the only variable measured that was not statistically different between the test stages at either work rate ($p = 0.27, 0.95$). Also, cycle rate was the only variable that approached significance between limb load conditions ($p=0.06$). Mean cycle rate values from each condition are displayed in Figure 3.1.

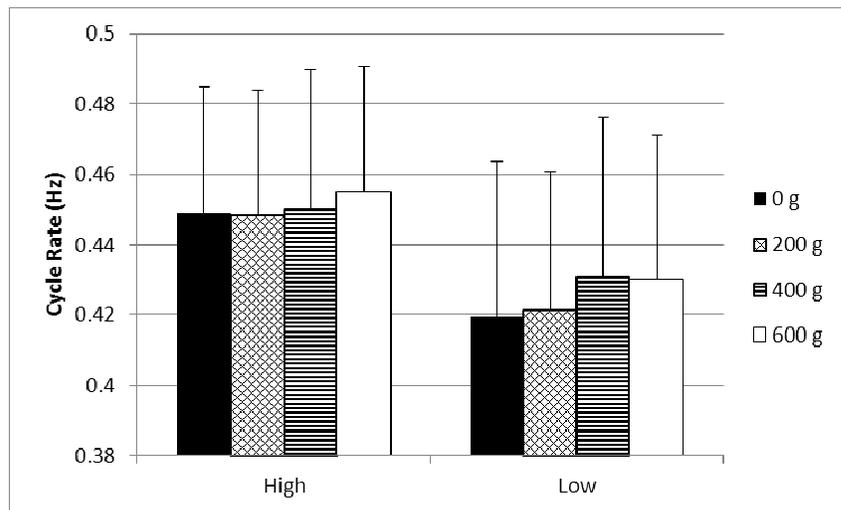


Figure 3.1. Mean (\pm SE) cycle rate values for each limb load condition at both high and low work rates. Cycle rates at the low work rate were all statistically lower ($p < 0.05$) than those at the high work rates.

Cycle rate was similar to the physiological variables in that there was no interaction between the limb loading condition and the work rate ($p=0.52$). However, cycle rate differed from the physiological variables in that there was a moderate positive

correlation with the limb loading conditions ($R^2 = 0.73$ and 0.83 for the high and low WR, respectively), but only weak correlations with the test sequence ($R^2 = 0.47$ and 0.44 for the high and low WR, respectively).

Discussion

The primary purpose of this investigation was to determine the effect of lower limb loading on skate roller skiing economy and gross movement kinematics. Four different limb loading conditions (0 g, 200 g, 400 g, and 600 g added per foot) were each evaluated at both a high and a low work rate. The study found no significant differences in VO_2 or cycle rate between the four limb loading conditions at either work rate. However, a sub-analysis found that all physiological variables significantly increased throughout the progression of test stages, except for RER, which steadily decreased. Interestingly, these changes were independent of limb loading conditions.

Physiological Variables

Primary Analysis. No significant differences existed between the four lower limb loading conditions at either work rate for any of the variables tested (VO_2 , HR, RER, Ve , or Bf). This finding was unexpected because previous research has found that added mass significantly increases VO_2 for other forms of locomotion. For example, it is well documented that VO_2 while running or walking increases by about 1% for every additional 100 g on each foot (Divert et al. 2008; Franz et al. 2012; Jones et al. 1984; Martin 1984; Ralston & Lukin 1969; Soule & Goldman 1969). In contrast, the present

study added as much as 600 g on each boot of skate roller skiers, yet did not find any significant changes in VO_2 . This finding may suggest that added lower limb mass has a smaller effect on skate roller skiing economy than running economy.

Sub-analysis. In the present study, it was observed that VO_2 , Ve , and Bf values tended to increase throughout test stages independent of limb loading condition. Consequently, a sub-analysis was performed to investigate the effect of testing sequence on the resulting physiological variables. This analysis found that all physiological variables had significant differences between test stages at both work rates. A Tukey's multiple comparisons test revealed a clear pattern that all values increased as the test progressed, except RER, which decreased throughout testing. These differences were observed independent from the order of limb loading conditions. In fact, HR and VO_2 each had a stronger correlation with the testing sequence than they did with the limb loading condition. The phenomenon of increasing cardiovascular values over time despite a constant work rate has previously been observed and is referred to as cardiovascular (CV) drift. Cardiovascular drift is primarily characterized by a continuous increase in HR such that a steady state is not attained. If subjects were experiencing CV drift, then it is possible that they were not in a steady state at the end of each stage of testing.

Reliability

Since it was an assumption of this study that subjects were at a steady state during the last two minutes of each stage, a reliability analysis was performed that compared the

mean cardiovascular values from the fourth minute of each stage with the mean values from the fifth minute of the same stage. The analysis consisted of an ANOVA and calculation of ICC and SEM values for each stage. This analysis found that mean HR values were significantly different in the fourth minute compared to the fifth minute in 9 of the 16 test stages. Eight of the nine differences in HR between the fourth and fifth minutes were increases. Clearly, steady state HR was not consistently attained during the test stages. In contrast, VO_2 had no significant differences between the fourth and fifth minute of any stage, while the remaining physiological variables (RER, V_e , Bf) each had significant differences in only 1-3 of the 16 test stages. All variables had high ICC and low SEM values for every stage. However, the calculation of both the ICC and the SEM involve comparing the variability within subjects to the variability between subjects. The variability between subjects in this study was high, especially between male and female subjects, so the high ICC and low SEM values are the result of large variability between subjects rather than small variability within. Thus, the ICC and SEM values are less informative than the ANOVA results. As a result, all variables except for HR can be considered steady state values during the last two minutes of each test stage.

Cardiovascular Drift. A gradual increase in HR is the characteristic feature of cardiovascular drift (Ekelund & Holmgren 1964; Ekelund 1967; Fritzsche 1998; Mattsson et al. 2011). In this study, HR clearly increased within each stage, as well as throughout the progression of test stages. Even though the remaining variables appeared to reach a steady state within each stage of this study, it is still likely that CV drift occurred. In fact, while increased VO_2 is usually observed with CV drift, it is typically a

small change (Ekelund & Holmgren 1964; Mattsson et al. 2010) and is not always significant over 60 minutes of exercise (Ekelund 1967). Meanwhile increases in other pulmonary measures such as V_e and B_f have been recorded in some (Ekelund & Holmgren 1964), but not all CV drift studies (Ekelund 1967; Mattsson et al. 2010). Therefore achievement of a steady state for two minutes at the end of a five minute stage is not strong enough evidence to reject the possibility that CV drift affected subjects in this study.

Fatigue is the most common cause of CV drift (Fritsche 1998). Therefore, CV drift usually occurs during high intensity or long duration exercise. In this study, however, subjects seemed to experience CV drift without roller skiing at a high intensity or for a long duration. The exercise intensity was below lactate threshold for all subjects, yet subjects were unable to attain a steady state HR even in the first five-minute stage at the high work rate. This finding conflicts with previous research, which has shown that a steady state heart rate can be maintained for at least 30 minutes while exercising at a work rate up to that at which anaerobic threshold is reached (Vobejda et al. 2006). Thus, it is unlikely that the drifting observed in this study was due to fatigue from an exercise bout of high intensity or long duration.

A more likely explanation for the CV drift is that subjects experienced mild hyperthermia, which is an increase in core body temperature. Hyperthermia has been shown to directly increase HR (Cooper et al. 1963) as well as increase sympathetic stimulation (Kenney et al. 1995). The sympathetic nervous system has effects on many cardiorespiratory factors, including HR, B_f , and V_e . Therefore, it is possible that

hyperthermia could have caused the cardiovascular drifting observed in this study through increased sympathetic nervous system stimulation. Unfortunately, no measurements of body temperature were taken during this study to confirm this speculation.

It would be somewhat surprising if the subjects experienced hyperthermia because they roller skied in moderate ambient temperatures (20-22°C) in front of a fan, whereas hyperthermia is generally observed while exercising in a hot (>30°C) environment (Claremont, Redden, & Brooks 1975). However, the ability to maintain a low core temperature during exercise requires adaptations. Specifically, exercise in warm temperatures increases the ability to dissipate heat by increased cutaneous blood flow and sweating (Saat et al. 2005). When the stimulus of heat exposure is removed, heat acclimatization decays within 1-4 weeks (Saat et al. 2005; Williams, Wyndham, & Morrison 1967). Testing for this study occurred in January and February, so any heat acclimatization that the subjects had from training in warm temperatures during the summer and fall had decayed.

Further, exercise in cold temperatures, as in cross country skiing, not only causes decay of heat acclimatization, but also leads to cold acclimatization. The adaptations associated with cold acclimatization are different from those associated with heat acclimatization. Primarily, when exercising in hot or moderate ambient temperatures, the primary method of heat dissipation is by vascular convection, requiring increased skin blood flow (Gonzalez-Alonzo 2012). In contrast, when exercising in cold ambient temperatures, the primary method of heat dissipation is simple conduction from muscle to

cutaneous tissue (Gonzalez-Alonzo 2012). Further, heat acclimatization allows individuals to maintain a lower skin temperature, whereas cold acclimatization has been shown to increase skin temperatures in both cold and moderate ambient temperatures (Maakinen et al. 2008). Since exercise in the cold uses a different mechanism for thermoregulation, cold acclimatization is very different from heat acclimatization.

In the current study, testing occurred in the middle of winter, and the subjects had been exercising outside in temperatures often well below 0°C for several months. Not only were subjects de-acclimatized to exercise in heat, but they also likely had some cold acclimatization from training outside. As a result, exercise in the moderate ambient temperatures could have induced a rise in sympathetic nervous stimulation as a result of mild hyperthermia. Increased sympathetic stimulation could have occurred quickly, which would explain the cardiac drift observed during the very first test stage. The increases in V_e and B_f between successive test stages can also be explained by hyperthermia as both variables have previously been reported to increase with elevated core temperature (Hayashi et al. 2006).

It is unlikely that the increase in VO_2 between test stages of this study is directly associated with an increase in core temperature because previous studies on mild hyperthermia have shown no association between core temperature and VO_2 (Hayashi et al. 2006). However, the increase in VO_2 might be indirectly caused by hyperthermia via a combination of several factors. First, it has been reported that the energy expended by respiratory muscles increases with increased V_e and B_f (Coast et al. 1993; Mattsson et al. 2010). Since both V_e and B_f increased throughout the test stages, it is possible that at

least a part of the increase in VO_2 between test stages may be explained by the elevated energy expenditure of respiratory muscles. However, Mattsson et al. (2010) reported that the drifting VO_2 during exercise at a constant work rate was only slightly affected by the energy expenditure of respiratory muscles. They postulated that VO_2 increases in their study were more likely due to decreased mitochondrial efficiency and decreased economy of movement resulting from changes in motor unit recruitment patterns. The change in motor unit recruitment was due to decreased force production by muscle fibers as a result of fatigue and muscle damage. In this study, subjects were well trained in skate skiing, so it is unlikely that a change in motor unit recruitment was required during a 40 minute bout of submaximal roller skiing. However, it is possible that the rise in temperature could have slightly decreased enzymatic efficiency within the mitochondria. Therefore, decreased mitochondrial efficiency might have contributed to the increases in VO_2 throughout the progression of testing. A final explanation is that the increases in VO_2 were simply due to an artifact of the metabolic system calculations. Specifically, the metabolic system only measures the volume of air expired and the composition of gases expired. It then uses this data to calculate a VO_2 . If the volume of expired air increases, the metabolic system calculations for VO_2 are inflated. Therefore, it is possible that the increased VO_2 observed was not actually caused by increases in oxygen consumption. In the present study, it is likely that the observed drift in VO_2 is due to a combination of these factors.

Evaluation of the physiological data in this study suggested that mild hyperthermia was the cause of the significant differences between test stages. Since the

cardiovascular responses were affected by hyperthermia, it cannot be concluded that the limb loads used in this study did not have any effect on skate roller skiing economy. In fact, the moderate correlation between the limb loading condition and the physiological variables suggest that the amounts of mass added to the lower limb in this study might cause significant differences, but they could not be identified because they were masked by CV drift. Clearly, more testing is necessary to acquire more information on the effects of lower limb loading on skate roller skiing economy.

Cycle Rate

Cycle rate was the only measured variable that approached significant changes between limb loading conditions. While non-significant, it is interesting to note that cycle rate tended to increase with greater limb loading, which is in contrast to some studies, which have observed an increase in step frequency while running with a limb load. It had been postulated that added mass on the distal end of the lower limb might reduce the speed at which the limbs would move, thus forcing a lower cycle rate. In contrast, the results showed a trend towards a greater cycle rate with increasing limb loading. However, it is unlikely that added mass on the lower limb directly increased cycle rate. Instead, it is more likely that the added mass directly decreased cycle length, which then caused the subjects to use a faster cycle rate to be able to maintain constant velocity. Unfortunately, there are no currently published studies investigating limb loading and cycle rate or cycle length with which to compare these findings. However, future research into the relationship between limb loading and cycle length would be valuable because cycle length has been positively correlated with ski race performance

(Bilodeau et al. 1996; Rundell & McCarthy 1996; Sandbakk et al. 2011). Therefore, heavier equipment might negatively impact performance if the extra mass on the lower limb forces skiers to use a shorter cycle length.

Cycle rates used during each stage at the low work rate were all significantly lower than the cycle rates used during each stage at the high work rate. This is in agreement with previous research, which has shown that a skier uses the same cycle rate at all work rates that have a constant external power demand (Reinking 2013). Further, a skier's cycle rate will increase when the external power demand increases.

Cycle rate was the only variable measured that was not significantly different between test stages. This finding supports the postulation that the physiological variables drifted due to hyperthermia because mild hyperthermia would not have affected cycle rate. If fatigue had been the factor causing the CV drift, then it is possible that kinematics, including cycle rate, might have changed due to different motor unit recruitment as the test progressed.

Future Considerations

In this study, it is possible that mild hyperthermia was the cause of gradual increases in all physiological variables throughout the progression of test stages independent of limb loading condition. It is also possible that the drifting masked the true effects of the lower limb loading. As a result, future testing is necessary to identify the effects of added mass on skate roller skiing economy independent of the effects of mild hyperthermia. In future testing, care should be taken to ensure that subjects are adequately acclimatized to the testing environment. One method of doing so would be to

perform the testing in the summer or fall when subjects have been training in warm air temperatures and have adapted accordingly. Alternatively, a cooler ambient temperature in the lab or greater wind chill by using a second fan could prevent hyperthermia during winter testing. Either of these options might reduce the cardiovascular drift and enable a better investigation of the effects of lower limb loading on skate roller skiing economy.

Conclusions

It has been suggested that the speed of skate ski races has increased as a result of improved skate skiing economy due to lighter equipment (Street 1992). Unfortunately, no studies exist that investigate the effect of the mass of skate ski equipment on any markers of performance. The present study added mass to the lower limbs of skate roller skiers to simulate the effects of heavier skate skiing equipment on roller skiing economy and gross movement kinematics.

This study found no significant differences in skate roller skiing economy or kinematics between lower limb loads of 0 g, 200 g, 400 g, and 600 g on each foot. However, there were significant differences between test stages independent of limb loading condition. Also, a reliability analysis between the fourth and fifth minutes of each test stage indicated that HR values were not at steady state during testing. Collectively, these findings suggest that subjects experienced cardiovascular drift. The most obvious increases over time were observed for mean HR values. This finding is consistent with previous research showing that the primary attribute of CV drift is a gradual increase in HR (Ekelund & Holmgren 1964; Ekelund 1967; Saat 2005). Oxygen

consumption, V_e , and B_f were stable enough to reach a steady state in each stage, but gradually increased throughout the progression of test stages. It was speculated that these changes were the result of greater stimulation by the sympathetic nervous system due to mild hyperthermia. Unfortunately, since VO_2 and HR values drifted throughout testing, the effects of the limb loading conditions might have been masked. As a result, further research is still necessary to identify the true effects of lower limb loading on skate roller skiing economy, and those studies should take care to ensure subjects are adequately acclimatized to the testing environment to prevent hyperthermia.

Finally, there was a non-significant trend that cycle rate increased with limb loading. This finding was opposite of what was expected, and the researchers do not have an explanation for this result. However, it is likely that the added mass indirectly affected cycle rate by directly decreasing cycle length. Further research is necessary to identify the effects of lower limb loading on gross movement kinematics.

4. CONCLUSIONS

Cross country skate ski race speed has increased over recent decades at a much greater rate than that of similar endurance based sports. Among the many factors that contribute to performance in cross country skiing, economy has been proposed as the primary cause of the dramatic increase in ski race speed (Street 1992). Skate skiing economy is affected by both internal factors, such as movement patterns and motor unit recruitment, and external factors, such as the coefficient of sliding friction and the mass of the equipment. Street (1992) specifically identified reductions in the mass of ski equipment as the most important change that led to increases in skate ski racing speed.

While no currently published studies exist that establish a relationship between skate skiing economy and the mass of skate skiing equipment, it has been well documented that equipment mass affects running and walking economy. In general, studies have found that for every 100 g added to each foot while walking or running, oxygen consumption (VO_2) increases by about 1% (Divert et al. 2008; Franz et al. 2012; Jones et al. 1984; Martin 1984; Ralston & Lukin 1969; Soule & Goldman 1969). Further, mass added to running shoes has been found to decrease stride rate (Divert et al. 2008; Lussiana et al. 2013). Since the metabolic and neural patterns of cross country skiing are similar to those of distance running (Stöggl & Müller 2009), it is likely that skate skiers respond to lower limb loading similar to runners. Therefore, changes in the mass of skate skiing equipment are expected to affect skate skiing economy and kinematics, and, possibly, ski racing performance.

This study added mass (0 g, 200 g, 400 g, and 600 g per foot) to the lower limbs of skate roller skiers to simulate heavier ski equipment and to determine the effects of heavier equipment on skate skiing economy and cycle rate. It was theorized that a greater limb load would increase VO_2 and HR at a constant work rate. However, the results of this study were that no significant differences existed between the different limb loading conditions. Interestingly, heart rate, VO_2 , and respiratory measures were significantly higher in later test stages compared to the first stages, regardless of the order of limb loading conditions. A reliability analysis was then performed to evaluate the assumption that subjects were in a steady state during each stage of the test. The results of the reliability analysis suggested that HR did not reach a steady state, but instead continued to increase in the last two minutes of at least half of the test stages. The combined results of the sub-analysis indicated that subjects experienced cardiovascular drift.

Cardiovascular drift typically results from fatigue due to an exercise bout being of high intensity or of long duration. However, it is unlikely that either the intensity or the duration of the exercise performed in this study was great enough to cause the cardiovascular drift. Alternatively, the cardiovascular drift observed in this study might have resulted from mild hyperthermia because the subjects were cold acclimatized but were being tested in moderate ambient temperatures. The effects of hyperthermia could explain the significant differences between the test stages as well as the HR drift that was observed within stages. Unfortunately, it is also possible that the limb loading conditions used in this study did have an effect on economy, but the effect could not be identified because it was masked by the cardiovascular drift. As a result, further testing is

necessary to identify the effects of added mass on the lower limbs while skate roller skiing. In future tests, researchers should attempt to minimize cardiovascular drift, which might involve adequately habituating the subjects to the temperature of the testing environment.

The final finding of this study was that gross movement kinematics showed a non-significant trend towards increased cycle rate with increases in limb loading. This finding is in contrast to some previous research on limb loading, which has found that added lower limb mass causes a decrease in stride rate while running (Divert et al. 2008; Lussiana et al. 2013). The researchers do not have an explanation for this discrepancy. Therefore, it would be valuable for future research to investigate the effects of lower limb loading on cycle rate and cycle length of skate skiing in greater detail.

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APPENDICES

APPENDIX A

SUBJECT CONSENT FORM

SUBJECT CONSENT FORM FOR PARTICIPATION IN HUMAN RESEARCH AT
MONTANA STATE UNIVERSITY – BOZEMAN

PROJECT TITLE: The effect of lower limb loading on economy and kinematics of skate roller skiing

FUNDING: This study is NOT a funded project

PROJECT DIRECTOR: Tyler Reinking, Masters Student
Department of Health and Human Development
Movement Science / Human Performance Laboratory
H&PE Complex, Montana State University
Bozeman, MT, 59717, 970-389-6187, tylerreinking@gmail.com

PURPOSE: The purpose of this project is to determine the effect of lower limb loading on energy expenditure and movement patterns. Additional mass attached to ski boots will simulate mass differences that are observed between different skate skiing equipment packages. The different amounts of mass added to your boots will allow us to evaluate changes in the energy cost of roller skiing as well as changes in body movements due to limb loading. You have been identified as a potential subject for this research project because of your skills in Nordic skiing.

Each participant is presented with this Informed Consent Document which explains the purpose of the testing, as well as risks and benefits associated with participation. Also, each participant is asked to complete a health history questionnaire for the purpose of identifying any health conditions that increase the risks associated with participation in this research project. If a concern is identified in your health history questionnaire, it is YOUR responsibility to acquire written medical clearance from your physician, and provide a copy of this written clearance to the Project Director, prior to participation. This procedure is in compliance with policies formulated by the American College of Sports Medicine.¹

PROJECT OUTLINE: There is no cost to you (the participant) and participation in this research project is voluntary. If you agree to participate you will be asked to make two separate visits to the Movement Science / Human Performance Lab at Montana State University – Bozeman, which will each last 60 to 90 minutes. Before arriving at the lab you should refrain from all forms of exercise for at least 24 hours. Also, you should refrain from ingesting any foods, drinks (with the exception of plain water), or medications, both prescription and over the counter medications, for at least 2 hours. Water will be allowed prior to and during the testing visits as desired. If any food, drink (other than water), or medication (including cold or allergy medication) is taken within the 2 hours prior to your test visit, please inform the Project Director BEFORE any testing begins and we will gladly reschedule your visit. If you use a rescue inhaler to treat asthma, make certain to bring the inhaler with you to the lab. You should arrive at the lab

¹ American College of Sports Medicine (2010). *ACSM's Guidelines for Exercise Testing and Prescription* (8th Edition). Williams & Wilkins, Philadelphia, PA.

ready to engage in high intensity exercise. Therefore, you should dress (lightweight exercise clothing suitable for roller skiing), eat, and drink fluids appropriately for the occasion.

The first visit to the lab will involve the completion of a roller skiing lactate threshold (LT) test. The primary purpose of this test is to identify the power demand at which your blood lactate concentrations increase rapidly. This will allow us to calculate your skiing intensity relative to your lactate threshold while roller skiing during visit two.

After measuring body height and weight, you will be allowed to warm-up roller skiing on the treadmill at 2° (3.5%) and at a self-selected speed for 10 minutes before starting the LT protocol. The test itself will start out easy and will gradually increase in difficulty with each stage as the treadmill speed is increased. Each stage will involve three minutes of roller skiing using the V2 technique followed by one minute of rest. During each one-minute rest, a fingertip blood sample will be collected from the left hand with the purpose of analyzing your blood lactate concentration. This procedure involves a prick at the end of the finger with a sterile lancet to produce a small droplet of blood that is then absorbed onto a blood lactate test strip. The finger is then wrapped with a bandage and the next stage begins. You will continue to progress to each additional stage until the Project Director observes a significant spike in blood lactate, which means that you have crossed lactate threshold. Once this happens, the LT protocol will be terminated and you will begin a 5-10 minute active recovery by roller skiing on the treadmill at 2° and 1.8 m/s (4 mph). These protocols typically last 3-5 stages for a total of 12-20 minutes.

The second visit will involve submaximal roller skiing under four different limb loading conditions (0 g, 200 g, 400 g, and 600 g on each boot; or 0 lbs, 0.44 lbs, 0.88 lbs, and 1.32 lbs on each boot), each at two work rates. The masses used are representative of possible variations observed in skate skiing equipment packages. This will allow us to determine the effect of added mass to the lower limb on economy and movement patterns.

Once again, you will begin by roller skiing to warm-up on the treadmill at 2° (3.5%) and at a self-selected speed for 10 minutes. After completion of the warm-up period, you will be allowed to rest for five minutes while the first limb load condition is placed upon you. Mass will be attached by taping disc weights to the lateral aspect of each of your boots at the ankle (specifically, the lateral malleolus). Once the mass is secure, you will roller ski for five minutes at one of the two work rates (3 m/s at 2° and 4° [6.7 mph at 3.5% and 7%] for males; 2 m/s at 2° and 4° [4.5 mph at 3.5% and 7%] for females). Then, the treadmill grade will be changed and you will roller ski for another five minutes at the second work rate. Upon completion of the second work rate, you will be given another five minutes to rest while the limb load is changed. Once again, you will roller ski for ten minutes, which will include five minutes at each work rate. The process will be repeated for all four limb load conditions and include a total of 40 minutes of roller skiing. Upon completion of the last stage, you will begin a 5-10 minute active recovery by roller skiing on the treadmill at 2° and 1.8 m/s (4mph).

For the duration of both visits, warm-up and recovery excluded, you will be breathing through a facemask and wearing a small backpack holding a portable metabolic system (< 6 lbs) so that the amount of oxygen you are using can be measured. At the same time, you will be wearing a heart rate monitor strap around your chest to measure heart rate via telemetry. Finally, to increase safety you will be wearing a climbing harness that attaches to an overhead suspension system to catch you in the event of a fall while roller skiing.

During the second visit, video recordings of you will be taken for analytical purposes. These videos will not be shared in any form. Also, you will have the option of allowing photographs to be taken of you during testing. If photographs are allowed, they may be shared during professional presentations of the research project.

POTENTIAL RISKS: You should be aware that submaximal LT tests may cause fatigue immediately after the tests and possibly during the next day. Treadmill testing protocols also involve a chance of precipitating a cardiac event (such as abnormal heart rhythms) or even death. However, the possibility of such an occurrence is very slight (less than 1 in 10,000). These statistics are for maximal treadmill tests and since you are participating in a submaximal test, these risks are even lower. Also, the risks are low since 1) you are in good physical condition with no known symptoms of heart disease and 2) the test will be administered by trained personnel familiar with the lab's emergency action plan. These risks are certainly no greater than those experienced by trained athletes in actual race competition. The measuring and safety devices (facemask, heart rate monitor, and climbing harness) may feel somewhat restricting and/or uncomfortable during testing, but all possible adjustments will be made to achieve the greatest comfort for you. The safety harness is worn to suspend you above the treadmill in the unlikely event of a fall on while roller skiing. While falling is always a possibility for any type of treadmill-based activity, a fall resulting in injury during the current study is unlikely but possible given your experience with roller skiing outdoors. Wearing the harness may feel somewhat odd at first, but the harness should not restrict your movement abilities whatsoever while roller skiing.

Approximately 3-5 drops of blood will be removed by fingertip sampling (i.e., 1 drop per finger puncture). This is a standard method used to obtain blood for routine hospital laboratory tests. You will experience pain when a sterile lancet goes into your finger. Other than momentary pain, the discomfort of the finger prick should be minimal. However, in about 10% of cases a small amount of bleeding under the skin will produce a bruise (hematoma). A small scar may persist for several weeks. The risk of local infection is less than 1 in 1,000.

All possible precautions will be taken to ensure your safety and make you feel comfortable before any testing takes place.

SUBJECT COMPENSATION: You will receive a copy of your LT test results directly. There are no other forms of compensation available for participating in this project.

BENEFITS: There are no direct benefits to you as a volunteer for this project. However, the Project Director, Tyler Reinking, is willing to discuss the interpretation of your own test results. You may contact Tyler Reinking by phone (970-389-6187) or E-mail (tylerreinking@gmail.com) at any time to discuss this option further.

In regards to overall project benefits, the conclusions of this study will be used to investigate the effect of limb loading on economy and kinematics of skate roller skiing. This information may be used to postulate the effect of differences in the mass of Nordic skiing equipment on markers of performance such as economy.

CONFIDENTIALITY: The data and personal information obtained from this project will be regarded as privileged and confidential. Your test results will not be released to anyone else except upon your written request/consent. Your right to privacy will be maintained in any

ensuing analysis and/or presentation of the data by using coded identifications of each person's data.

FREEDOM OF CONSENT: You may withdraw consent for participation in writing, by telephone, or in person without prejudice or loss of benefits (as described above). Participation in this project is completely voluntary.

In the UNLIKELY event that your participation in the project results in physical injury to you, the Project Director will advise and assist you in receiving medical treatment. No compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of your participation in the project. Additionally, no compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of traveling to and from you appointments at the Movement Science / Human Performance Laboratory. Further information regarding medical treatment may be obtained by calling the Project Director, Tyler Reinking, at 970-389-6187 or the Lab Director, Dan Heil, at 406-994-6324. You are encouraged to express any questions, doubts, or concerns regarding this project. The Project Director will attempt to answer all questions to the best of his ability prior to any testing. The Project Director fully intends to conduct the study with your best interest, safety, and comfort in mind. If you have additional questions about the rights of human subjects you can contact the Chair of the Institutional Review Board, Mark Quinn, at 406-994-4707 or mquinn@montana.edu.

PROJECT TITLE: The effect of lower limb loading on economy and kinematics of skate roller skiing

STATEMENT OF AUTHORIZATION

I have read the above and understand the discomforts, inconvenience, and risk of this study. I, _____ (*print your name*), agree to participate in this research. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

Signature of Participant

Date

Signature of Parent or Guardian (if under 18)

Date

Print Name of Parent or Guardian

Relationship to Subject

Investigator

Date

Please initial one of the following:

I give permission for photographs to be taken of me during this project with the understanding that these photographs may be used in professional presentations.

I DO NOT give permission for photographs to be taken of me during this project.

APPENDIX B

HEALTH HISTORY QUESTIONNAIRE

Health History Questionnaire (HHQ) - Montana State University Movement Science / Human Performance Laboratory

INSTRUCTIONS

Complete each of the following questions as accurately as possible by filling in the blanks or checking the most appropriate box. All information provided is confidential and no information will be released without your written consent.

Today's Date _____

GENERAL INFORMATION

Mr. Ms. Miss Mrs. Dr.

Last Name _____ First Name _____

Mailing Address _____

Home Phone _____ Office Phone _____

Occupation _____

Employer _____

Person to Contact in Emergency: Name _____

Relationship _____

Phone _____

▪ *Descriptive information:*

Gender: Male Female Body Weight _____

Age _____ Date of Birth _____ Body Height _____

▪ *Why are you filling out this questionnaire?*

- You have volunteered for a research study or project.
- You are being screened for fitness testing in the Movement Science Lab.
- Other reason... _____

MEDICAL HISTORY

Name of your physician _____

(Address/phone?) _____

▪ *Family History:*

Did your father, or other first degree male relative (like a brother) die before the age of 55?

No Yes If Yes, cause? _____

Age at death? _____

Which relative? _____

Did your mother, or other first degree female relative (like a sister) die before the age of 65?

No Yes If Yes, cause? _____

Age at death? _____

Which relative? _____

▪ *List any food or drug allergies:*

▪ *List any medication you are currently taking (non-prescription and prescription, including oral contraceptives). Please comment on the reason for each medication.*

▪ *Please describe any recent illnesses, hospitalizations, or surgical procedures:*

▪ Any of these health symptoms that occurs frequently (ranked as either a 4 or 5 below), either at rest or during physical exertion, is the basis for a prompt medical evaluation. Circle the number indicating how often you have each of the following:

	0 = Never	1 = Practically never	2 = Infrequently	3 = Sometimes	4 = Fairly often	5 = Very often
a. Coughing up blood.	0	1	2	3	4	5
b. Abdominal pain.	0	1	2	3	4	5
c. Low-back pain.	0	1	2	3	4	5
d. Chest pain.	0	1	2	3	4	5
e. Neck, jaw, arm, or shoulder pain.	0	1	2	3	4	5
f. Leg pain.	0	1	2	3	4	5
g. Swollen joints, especially the ankles.	0	1	2	3	4	5
h. Feel faint.	0	1	2	3	4	5
i. Feeling of dizziness.	0	1	2	3	4	5
j. Breathless with slight exertion.	0	1	2	3	4	5
k. Palpitation or fast heart rate.	0	1	2	3	4	5
l. Unusual fatigue with normal activity.	0	1	2	3	4	5
m. Abnormal/labored breathing at night.	0	1	2	3	4	5

For any score of "4" or higher, use the space below to explain the frequency and the conditions under which you experience that particular symptom:

· Please indicate which of the following for which **you have been diagnosed or treated** by a physician or health professional. Please be as complete as possible.

Check if "Yes" If "Yes", please comment further...

- Alcoholism _____
- Anemia, sickle cell _____
- Anemia, other _____
- Asthma _____
- Back strain _____
- Blood pressure - High? _____
Low? _____
- Bronchitis _____
- Cancer _____
- Cirrhosis, liver _____
- Cholesterol - High? _____
- Concussion _____
- Congenital defect _____
- Diabetes Type? _____
- Emphysema _____
- Epilepsy _____
- Eye problems _____
- Gout _____
- Hearing loss _____
- Heart problems _____
- Hypoglycemia _____
- Hyperlipidemia _____
- Infectious mononucleosis _____
- Kidney problems _____
- Menstrual irregularities _____
- Mental illness _____
- Neck strain _____
- Obesity _____
- Phlebitis _____
- Rheumatoid arthritis _____
- Stroke _____
- Thyroid problems _____
- Ulcer _____
- Other _____

BLOOD CHEMISTRY PROFILE

- Have you ever had a fasting blood sample analyzed for cholesterol? Yes No

If "Yes", when was last time your blood was analyzed? _____

If "Yes", please provide as much detail as possible with regard to the specific blood components requested below (most recent test results only). Ideally, we would like both the numerical value of the test result AND the units of the measurement (the units are typically reported along with the numerical value of the test result).

· Total serum cholesterol	_____	units? _____
· HDL (high density lipoprotein)	_____	units? _____
· LDL (low density lipoprotein)	_____	units? _____
· VLDL (very low density lipoprotein)	_____	units? _____
· Triglycerides	_____	units? _____
· Blood glucose	_____	units? _____
· Hemoglobin	_____	units? _____
· Hematocrit	_____	units? _____
· Iron	_____	units? _____

HEALTH-RELATED BEHAVIORS

- Do you now smoke? Yes Infrequently No

If "Yes" or "Infrequently", indicate the number smoked per day (on average):

Cigarettes: 40 or more 20-39 10-19 1-9

Cigars/pipes - describe: _____

- Have you recently quit smoking? Yes No

If "Yes", how long ago did you quit? _____ years _____ months

- Do you currently work in an environment where smoking is allowed?

Yes No

If "Yes", where do you work AND how frequently do you work in this environment?

- Do you drink alcoholic beverages on a regular basis? Yes No
(ie. at least once/week)

If "Yes", please answer the following:

1) How frequently do you drink?

2) What alcoholic beverages do you typically consume?

- Have you **exercised** regularly in the past 4 weeks? Yes No

If "Yes", describe in terms of frequency, duration, intensity, and type of exercise:

- Do you consider yourself **physically active** due to work-related demands, home or farm chores, etc.?

Yes No

If "Yes", describe in terms of frequency, duration, intensity, and type of exercise:

- Please describe anything not already described on this questionnaire that might cause you problems during exercise (use the space below).

- Are there any other health-related problems or concerns NOT addressed on this questionnaire that we should know about?

Yes No

If "Yes", please describe: