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THE ROLLING RESISTANCES OF ROLLER SKIS AND THEIR EFFECTS ON HUMAN PERFORMANCE DURING TREADMILL ROLLER SKIING

Mats Ainegren

Supervisors:
Associate Professor Peter Carlsson, Mid Sweden University
Ph.D. Marko Laaksonen, Mid Sweden University

Department of Engineering and Sustainable development
Mid Sweden University, SE-831 25 ÖSTERSUND, Sweden

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Mats Ainegren

Department of Engineering and Sustainable development
Mid Sweden University, SE-831 25 Östersund
Sweden

Telephone: +46 (0)771-975 000

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ABSTRACT

Modern ski-treadmills allow cross-country skiers, biathletes and ski-orienteers to test their physical performance in a laboratory environment using classical and freestyle techniques on roller skis. For elite athletes the differences in performance between test occasions are quite small, thus emphasising the importance of knowing the roller skis' rolling resistance coefficient, μ_R, in order to allow correct comparisons between the results, as well as providing the opportunity to study work economy between different athletes, test occasions and core techniques.

Thus, one of the aims of this thesis was to evaluate how roller skis' μ_R is related to warm-up, mass, velocity and inclination of the treadmill. It was also necessary to investigate the methodological variability of the rolling resistance measurement system, RRMS, specially produced for the experiments, with a reproducibility study in order to indicate the validity and reliability of the results.

The aim was also to study physiological responses to different μ_R during roller skiing with freestyle and classical roller skis and techniques on the treadmill as a case in which all measurements were carried out in stationary and comparable conditions.

Finally, the aim was also to investigate the work economy of amateurs and female and male junior and senior cross-country skiers during treadmill roller skiing, i.e. as a function of skill, age and gender, including whether differences in body mass causes significant differences in external power per kg due to differences in the roller skis' μ_R.

The experiments showed that during a warm-up period of 30 minutes, μ_R decreased to about 60-65% and 70-75% of its initial value for freestyle and classical roller skis respectively. For another 30 minutes of rolling no significant change was found. Simultaneous measurements of roller ski temperature and μ_R showed that stabilized μ_R corresponds to a certain running temperature for a given normal force on the roller ski. The study of the influence on μ_R of normal force, velocity and inclination produced a significant influence of normal force on μ_R, while different velocities and inclinations of the treadmill only resulted in small changes in μ_R. The reproducibility study of the RRMS showed no significant differences between paired measurements with either classical or the freestyle roller skis.

The study of the effects on physiological variables of ~50% change in μ_R, showed that during submaximal steady state exercise, external power, oxygen uptake, heart rate and blood lactate were significantly changed, while there were non significant or only small changes to cycle rate, cycle length and ratings of perceived exertion. Incremental maximal tests showed that time to exhaustion was significantly changed and this occurred without a significantly changed maximal power, maximal oxygen uptake, maximal heart rate and blood lactate, and that the influence on ratings of perceived exertion was non significant or small.

The final part of the thesis, which focused on work economy, found no significant difference between the four groups of elite competitors, i.e. between the two genders and between the junior and senior elite athletes. It was only the male amateurs who significantly differed among the five studied groups. The study also showed that the external power per kg was significantly different between the two genders due to differences in body mass and μ_R, i.e. the lighter female testing groups were roller skiing with a relatively heavier rolling resistance coefficient compared to the heavier testing groups of male participants.

Keywords: Blood lactate, cycle length, cycle rate, heart rate, oxygen uptake, performance, power, roller skis, rolling resistance, ratings of perceived exertion, work economy

SAMMANFATTNING

Utvecklingen av moderna rullband för rullskidåkning har gjort det möjligt för längdskidåkare, skidskyttar och skid-orienterare att testa sin fysiska förmåga i laboratoriemiljö genom rullskidåkning i klassisk och fri stil. För elit-skidåkare är de fysiologiska skillnaderna relativt små mellan olika testtillfällen, vilket innebär att det är viktigt att test-rullskidornas rullmotstånds-koefficient, μ_R, kontrolleras i samband med tester för att möjliggöra för korrekta jämförelser mellan olika testresultat.

Syftet med denna licentiat avhandling var därför att undersöka rullskidors μ_R som funktion av uppvärmning, massa (normalkraft), hastighet och lutning på rullande band. Det var även viktigt att undersöka metodfelet för den specifika utrustning, RRMS, som användes vid experimenten, genom en reproducerbarhets-studie, för att undersöka validiteten och reliabiliteten för metoden.

Syftet var också att studera fysiologiska effekter som funktion av olika μ_R vid rullskidåkning på rullande band, dvs i en miljö där alla mätningar genomfördes under standardiserade och jämförbara förhållanden.

Slutligen, var syftet även att undersöka arbetsekonomin mellan amatörer och kvinnliga och manliga junior- och senior elitskidåkare vid rullskidåkning på rullande band, dvs arbetsekonomi som funktion av färdighetsnivå, ålder och kön. Dessutom, undersöktes om skillnader i försöksgruppernas kroppsmassor medförde skillnader i effekt per kg pga skillnader i rullskidornas μ_R.

Experimenten visade att under de första 30 minuterna av kontinuerligt rullande så sjönk rullskidornas μ_R signifikant till 60-65% och 70-75% av deras initiala värden, för fristils- respektive klassiska rullskidor. För de efterföljande 30 minuterna förekom ingen signifikant förändring av μ_R. Samtida mätningar av μ_R och rullskidans temperatur visade att en stabil μ_R motsvarade en viss temperatur för en given normal kraft. Undersökandet av olika normalkrafters, hastigheters och lutningars påverkan på μ_R resulterade i en signifikant, negativ korrelation för μ_R som funktion av olika normalkrafter, medan olika hastigheter och lutningar endast medförde små förändringar av μ_R. Reproducerbarhets-studien av den metod som användes för att mäta rullskidornas μ_R visade inga signifikanta skillnader mellan parade mätningar för vare sig fristils- eller klassisk rullskida.

Studien som undersökte fysiologiska skillnader av olika μ_R visade, vid protokoll med konstanta submaximala arbetsbelastningar, att yttre effekt, syreupptagning, hjärtfrekvens och blodlaktat förändrades signifikant vid ~50% förändring av μ_R, medan försökspersonernas frekvens och sträcka per frekvens samt skattning av upplevd ansträngning resulterade i mestadels icke signifikanta eller små förändringar. Protokoll där arbetsbelastningen stegvis ökade till utmattning, för försökspersonerna, resulterade i signifikant förändrad tid till utmattning, vid ~50% förändring av μ_R. Detta inträffade utan

signifikant skillnad i maximalt syreupptag, maximal hjärtfrekvens och blodlaktat, vilket även mestadels gällde för skattning av upplevd ansträngning.

Den avslutande studien som undersökte arbetsekonomi, fann ingen signifikant skillnad mellan de fyra grupperna av elit-skidåkare, dvs det var ingen skillnad mellan de båda könen och ej heller mellan juniorer och seniorer. Det var endast gruppen bestående av manliga amatörer som skiljde sig signifikant mellan de fem grupper som studerades. Studien visade också att yttre effekt per kg kroppsmassa signifikant skilde sig mellan könen, vilket berodde på skillnader i kroppsmassa och μ_R, dvs de mindre vägande kvinnliga test-grupperna åkte med en något tyngre rullmotstånds-koefficient i jämförelse med de något tyngre vägande test-grupperna med manliga försökspersoner.

LIST OF PAPERS

This licentiate thesis is based on the following three papers, herein referred to by their Roman numerals. The articles are reprinted with permission from the publishers.

Paper I Rolling resistance for treadmill roller skiing.
Mats Ainegren, Peter Carlsson, Mats Tinnsten
Sports Eng (2008) 11:23-29.

Paper II Roller ski rolling resistance and its effects on elite athletes´ performance.
Mats Ainegren, Peter Carlsson, Mats Tinnsten
Sports Eng (2009) 11: 143-157.

Paper III Work economy of amateur and elite cross-country skiers during treadmill roller skiing.
Mats Ainegren, Peter Carlsson, Mats Tinnsten, Marko Laaksonen
Proceedings of the 4th Asia-Pacific Congress on Sports Technology (APCST 2009), Honolulu, Hawaii, USA, 21-23 September 2009: 483-487.

ABBREVIATIONS

Biomechanics

α	Inclination of the treadmill [°]
CR	Cycle rate [$1 \cdot min^{-1}$]
CL	Cycle length, [$m \cdot C^{-1}$]
g	acceleration of gravity [$9.81\ m \cdot s^{-2}$]
m	mass [kg]
N	Normal force
P	Power from elevating the transported mass against gravity
$P\mu_R$	Power from overcoming the roller skis rolling resistance coefficient
$P_{W\ EXT}$	External power, $P + P\mu_R$ [W]
$p_{W\ EXT}$	External power, $P + P\mu_R$ [$W \cdot kg^{-1}$]
$P_{W\ MAX}$	External, maximal, power [W]
TTE	Time to exhaustion [min.s]
T	Temperature [°C]
v	velocity, speed of the treadmill [$km \cdot h^{-1}$] [$m \cdot s^{-1}$]
μ_R	Rolling resistance coefficient

Subject identification

MA	Male amateurs
MS	Male senior elite cross-country skiers and biathletes
MJ	Male junior cross-country skiers and biathletes aiming for an elite career
WS	Women senior elite cross-country skiers and biathletes
WJ	Women junior cross-country skiers and biathletes aiming for an elite career

Physiology

B-Hla	Blood lactate concentration [$mmol \cdot L^{-1}$]
HR	Heart rate [$1 \cdot min^{-1}$]
HR_{MAX}	Maximal heart rate [$1 \cdot min^{-1}$]
K_{CAL}	Calorie expenditure $\cdot$ 1000
P_{GROSS}	Gross energy expenditure [$K_{CAL} \cdot min^{-1}$]
$P_{W\ INT}$	Internal power, $P_{GROSS}/0.01433$ [W]
$p_{W\ INT}$	Internal power [$W \cdot kg^{-1}$]
RPE_{BREATH}	Ratings of perceived exertion, breathing [scale 6-20]
RPE_{ARM}	Ratings of perceived exertion, arms [scale 6-20]
RPE_{LEG}	Ratings of perceived exertion, legs [scale 6-20]
RQ	Respiratory quotient [VCO_2/VO_2]
VCO_2	Carbon dioxide production [$L \cdot min^{-1}$]
VO_2	Oxygen uptake [$L \cdot min^{-1}$]
vO_2	Oxygen uptake [$mL \cdot kg^{-1} \cdot min^{-1}$]
$VO_{2\ MAX}$	Maximal oxygen uptake [$L \cdot min^{-1}$]
$vO_{2\ MAX}$	Maximal oxygen uptake [$mL \cdot kg^{-1} \cdot min^{-1}$]

Statistics

p	Significant coefficient
r	Correlation coefficient
SD	Standard deviation
TEM	Technical error of measurement

PREFACE

My interest in roller skis' rolling resistances began in the early 2000s, when I started to work with the physiological testing of elite athletes performing roller skiing on a ski-treadmill. At that time there was no product on the market that was designed for checking the roller skis' rolling resistances.

During testing I frequently asked myself;

"How large is the day to day variation in rolling resistance of the roller skis that we are using during testing and what happens to the rolling resistance after weeks and months of usage? Are there significant differences in rolling resistance between different pairs of roller skis of the same type coming from the same manufacturer? What about the rolling resistance of a new pair of roller skis brought in for usage during testing when the pair we are using now is wearied out?"

And, the central issue;

"What about the physiological responses to the eventual changes in the roller skis rolling resistance?"

Based upon the measurements of oxygen consumption, comparisons were sometimes made between different test occasions and skiers with the aim of investigating individual work economy. "Is it valid to do what we are doing, comparing work economy between test occasions and subjects without knowing whether the roller skis' rolling resistance is the same and how the rolling resistance is influenced by skiers with different body masses?"

Some journal papers described how researchers were connecting a subject to a sensor with a line while rolling on a treadmill but this method did not seem to have the desired level of accuracy and it showed diverging results for the influence on rolling resistance of mass, velocity and incline.

All the questions above were also coming from the overall speculations;

"Is it such a good idea to carry out physiological tests on a treadmill without knowing the reproducibility of the roller skis' rolling resistance and thereby the accuracy of the method? Is this testing method for cross-country skiers, biathletes and ski-orienteers to be regarded as a scientific method if not all equipment can be calibrated and/or controlled?"

In 2003, I received an offer to move to Östersund and start employment at the Swedish Winter Sports Research Centre, which was then a project initiated by the regional sports association with financial support from the European Union. The offer came from the project manager, Bertil Karlsson, and the assistant project manager, and project manager of the Ski-University, Anders Edholm. This was at a time when the project was new and my only colleague at the time at the laboratory, future Ph.D. student Glenn Björklund, and myself were continuously building the laboratory in parallel with the testing of Swedish elite athletes in winter sports. We were fortunate to have greatest support from the world famous physiologist, Professor Bengt Saltin, Copenhagen Muscle Research Centre, also a

Guest Professor at Mid Sweden University.

One day, when having lunch at a restaurant, I came in contact with Professor Mats Tinnsten, Dep. of Eng. and Sust. Dev. (then Ass. Prof. at Dep. of Eng., Phys. and Math.). Mats Tinnsten was very interested in the laboratory and became especially interested when I described the problem of not being able to control the reproducibility of the roller skis' rolling resistance. It was also Mats who later on invented the idea for the construction of the roller ski rolling resistance measurement system (RRMS) used in the experiments in this thesis. Another person who soon joined our small group that was interested in roller skis' rolling resistance, and the reproducibility of the physiological measurements, was Mats colleague, and my upcoming main supervisor, Ass. Professor Peter Carlsson. Without the support of Mats, Peter and Bengt, the studies within this thesis would probably never have started.

This licentiate thesis thus investigates several of the questions raised above, by experiments mostly carried through by myself in the laboratory at the Swedish Winter Sports Research Centre, Mid Sweden University.

The future, post licentiate thesis, is intended to study performance during treadmill roller skiing, not only due to rolling resistance but also as a function of grip in classical cross-country skiing.

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1 INTRODUCTION

Physiological tests of elite athletes are common in exercise laboratories, due to the possibility of using a wide range of advanced equipments for different types of analyses and the advantage of comparisons that use relatively stationary and reproducible conditions (Baumgartl *et al.* 1990, Saunders *et al.* 2004, Holmberg *et al.* 2005). Over the last few decades specific testing methods for cross-country skiers, biathletes and ski-orienteers have become possible due to the development of treadmills that allow roller skiing using classical and freestyle techniques (Rundell 1995, Calbet *et al.* 2005, Holmberg *et al.* 2005).

For elite athletes the differences in performance between test occasions are quite small, thus emphasising the importance of knowing the roller skis' rolling resistance coefficient, μ_R, in order to allow correct comparisons between the test results. Thus, using roller skis results in a need to control their μ_R, which is of great importance in securing good reproducibility for this specific method, and also providing the opportunity to study work economy between different test occasions and core techniques.

Only a few authors have studied the μ_R of roller skis. The method described in earlier studies was based on force measurements that were carried out using a skier wearing a backpack filled with varying mass. The skier was instructed to distribute mass evenly on both roller skis whilst rolling on the treadmill (Hoffman *et al.* 1990b). However, the data presented when using this method showed varying results and no reliability testing for the method was presented (Hoffman *et al.* 1990b and 1995, Millet *et al.* 1998). A similar method, investigating roller blades' rolling resistance on outdoor surface, showed a variability of 20% (de Boer *et al.* 1987).

Hoffman *et al.* (1990b) observed that the coefficient of roller skis' rolling resistance (in Hoffman *et al.* 1990b called the dynamic friction coefficient μ) was not dependent on the velocity but increased with increasing body mass. However, in 1994 and 1995 Hoffman *et al.* found that body mass did not affect μ_R, but that μ_R was related to speed. Millet *et al.* (1998), on the other hand, found that μ_R was not dependent on velocity for low-resistance roller skis but dependent on velocity for high-resistance roller skis.

In 1990b, Hoffman *et al.* wrote that they allowed the roller skis to become warm prior to making force measurements but they do not describe the amount of time that was needed nor any temperature registrations, and neither do they describe how big the differences in μ_R were between the cooler and the warmer roller ski. If rolling resistance is temperature dependent, it could be of great importance when comparing physiological results, since the roller skis might have different initial temperatures depending on different previous usages.

There are few studies which have investigated the biomechanical and physiological responses to different μ_R. However, the μ_R measurements were made on a ski treadmill, while the biomechanical and physiological measurements were made outdoors, in other environments and on other surfaces, i.e. on an asphalt oval (Millet *et al.* 1998) and on an asphalt roadway (Hoffman *et al.* 1998).

The probably most frequently measured, and important, variable in endurance sports is the maximal oxygen uptake, $VO_{2\ MAX}$, due to its high correlation to performance for endurance athletes and cross-country skiers in particular (Saltin and Åstrand 1967, Bergh 1987, Ingjer 1991, Saltin 1997, Bergh and Forsberg 2000). Other commonly investigated variables within endurance sports are power output, heart rate, blood lactate concentration, ratings of perceived exertion and stride frequency and stride length (Gore 2000, McArdle 2001).

Although an extremely high $VO_{2\ MAX}$ value is essential for peak performance, it cannot be fully utilized during endurance competitions, with the exception of for very short periods of time and shorter distances, due to muscle fatigue and glycogen depletion (Allen *et al.* 2008). Thus, the ability to utilize a high fraction of the $VO_{2\ MAX}$ also becomes very important and results from laboratory tests have been compared with field tests in environments similar to competitions for such comparisons (Niinimaa *et al.* 1978, 1979, Mygind *et al.* 1994, Welde *et al.* 2003, Larsson and Henriksson-Larsen 2005).

The utilization fraction is also affected by the subject's work economy, which has been investigated using various definitions as movement economy (Kvamme *et al.* 2005), mechanical efficiency (Niinimaa *et al.* 1979), energy cost (Welde *et al.* 2003) and delta efficiency (Hoffman *et al.* 1995). Regardless of the definition, the studies are based upon the oxygen cost for a given workload and some of the papers also consider the mechanical efficiency, i.e. the relationship between energy input and energy output.

The work economy of cross-country skiing has been studied outdoors during skiing on snow (Bergh 1987, MacDougall *et al.* 1979) and on bituminous concrete (Hoffman *et al.* 1990a) and asphalt surfaces by using roller skis (Hoffman *et al.* 1990b, Hoffman *et al.* 1998). It has also been studied during treadmill roller skiing over some different core techniques (Hoffman *et al.* 1994, Hoffman *et al.* 1995, Kvamme *et al.* 2005), between the two genders (Hoffman *et al.* 1995) and, on biathletes, with and without rifle carriage (Rundell, 1998). If roller skis' μ_R is found to be influenced by different masses, one should also take into consideration the eventual differences in external power, $P_{W\ EXT}$, for overcoming the roller skis' rolling resistance, $P\mu_R$, if differences exist in the athletes´ body masses. This is not always investigated and in Rundell (1998) the results were determined on the basis of the men's use of one type of roller ski of unknown μ_R, and the women's use of another type, also of unknown μ_R. The two types of roller skis came from different manufacturers. In Hoffman *et al.* (1990a) the subjects used four different models of roller skis of unknown μ_R.

Therefore, one of the aims of this thesis is (I) to evaluate roller skis' μ_R using specific equipment for rolling resistance measurements, independently of human influence. This would be of great importance in clarifying how the rolling resistance coefficient of roller skis is related to mass, velocity and incline. Moreover, a warm-up study will investigate whether and, if so, how long it takes until the roller skis reach stationary conditions (equilibrium), i.e. are stable as regards μ_R and temperature. It is also necessary to investigate the methodological variability of the specific equipment for rolling resistance measurements with a reproducibility study, in order to indicate the validity and reliability of the results.

The aim is also (II) to study the physiological responses to different rolling resistances in the case where all measurements use stationary and comparable conditions, including whether a significantly different μ_R causes significant changes to oxygen uptake, heart rate, blood lactate, power, ratings of perceived exertion, cycle rate and cycle length during submaximal exercise. Time to exhaustion and maximal power on incremental maximal tests also need to be addressed. In addition, the dependence of maximal oxygen uptake on μ_R has to be addressed.

Finally, the aim is also (III) to investigate work economy during treadmill roller skiing as a function of skill, age and gender, including whether eventual differences in the roller skis' $\mu_{R,}$ due to differences in body mass, cause significant differences in external power per kg.

2 EXPERIMENTAL STUDIES

2.1 Equipment

All experiments were carried out on a motorized treadmill (RL 3500, 300 · 250 [cm], Rodby Innovation AB, Vänge, Sweden). The inclination and velocity were checked using a digital water slope and a tachometer respectively. The experiments used classical (1.1 kg per roller ski) and freestyle (1.0 kg per roller ski) roller skis (Pro-Ski, Sterners, Nyhammar, Sweden) with different rolling age varying from ten hours up to several hundred hours. The roller skis were equipped with medium hard rubber wheels (classical, ∅65 mm, width 50 mm) and thermoplastic polyurethane 80 degree shore A wheels (freestyle, ∅70 mm, width 30 mm) and with conventional roller bearings in the hub. The length between the axes of the forward and rear wheel was 720 mm and 613 mm for classical and freestyle roller skis respectively. The horizontal length, at inclination zero, between the axis of the forward wheel and the vertical line threw the centre of mass, put on top of the roller skis, was 510 mm and 380 mm for classical and freestyle roller skis respectively.

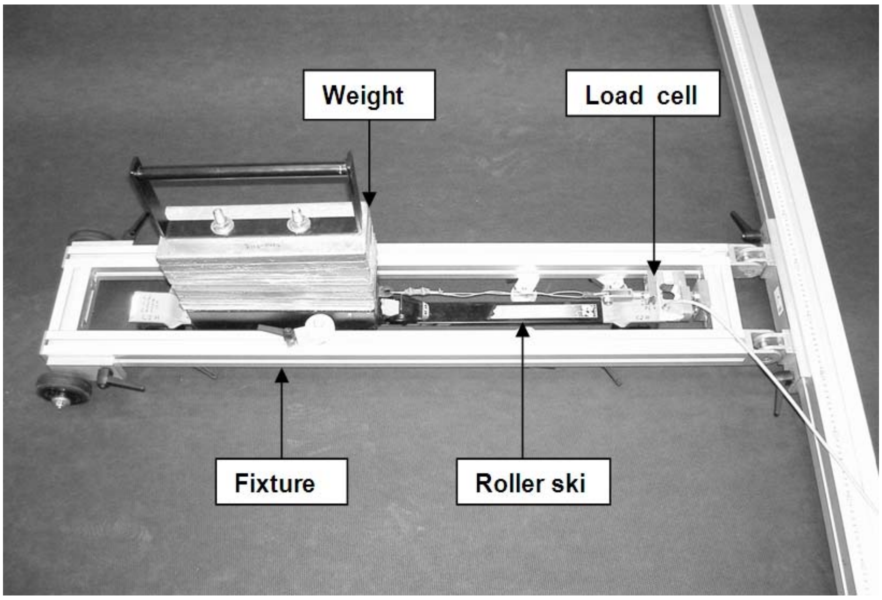

Figure 1. Roller ski with load of lead plates and the RRMS equipment for rolling resistance measurements.

Rolling resistance was measured on the treadmill surface with the roller skis mounted in a fixture specially produced for these types of measurements (RRMS, Side System AB, Oviken, Sweden), see Fig. 1. Samples were taken with an S2 force transducer (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) at a rate of 1 Hz. The temperature measurements were made with a digital thermometer and sensor (GMH 3250, thermocouple type K with a rate of 0.33 Hz) from Greisinger electronic GmbH, Regenstauf, Germany.

The metabolic measurements for oxygen uptake (VO_2) and heart rate (HR) were made using an ergo-spirometry system (AMIS 2001, Innovision A/S, Odense, Denmark) (Jensen *et al.* 2002) and a Polar heart rate monitor (Polar Electro OY, Kempele, Finland). Venous blood samples for analyses of blood lactate (B-Hla) were made using 2 ml syringes from a 200 cm (1.5 ml) extension set (ALARIS medical UK ltd, Hampshire, UK) connected to a catheter (BD Venflon^{TM} Pro 1.3 x 32mm, Becton Dickinson, Helsingborg, Sweden) in vena cephalic and analysed with Biosen 5140 (EKF-Diagnostic, Magdeburg, Germany). Between the samples the system was flushed with isotonic saline to avoid coagulation. Thus, each sampling started with discharging a volume greater than 3 ml before the actual sample was taken. Measurements of mass and height were made with SECA equipment (Ergonordic, Bromma, Sweden). The subjects used their own ski poles with a special tip for the treadmill's rubber surface (Jakobsen V, Oslo).

2.2 Statistical analyses

The statistical analyses were carried out using SPSS for Windows statistical software Release 12.0.1 (Part I) and 16.0 (Part II and Part III) (SPSS Inc., Chicago, Illinois). In Part I the statistics were calculated using paired Student *t* test and Pearson correlation coefficient *r*. The methodological error was calculated as an absolute error using Technical Error of Measurement, TEM, (Gore 2000), where di is the difference between the first and second measurement and *n* is the number of paired measurements.

$$TEM = \sqrt{\frac{\sum di^2}{2n}} \qquad (1)$$

and an relative error as %*TEM*

$$\%TEM = \frac{2 \cdot TEM}{(M1 + M2)} \cdot 100 \qquad (2)$$

In Part II and Part III, one-way ANOVA with Bonferroni post hoc tests were used for comparison within subjects between the different test occasions and between the different groups, respectively. The Pearson correlation coefficient *r* was used to measure the linear dependence of μ_R as a function of different normal forces. In all statistical analyses the significance level was set to $p < 0.05$.

2.3 Part I. Roller skis' rolling resistance coefficients

2.3.1 Mechanics of the roller ski

There is a schematic sketch of the experimental setup in the free-body diagram in Fig. 2.

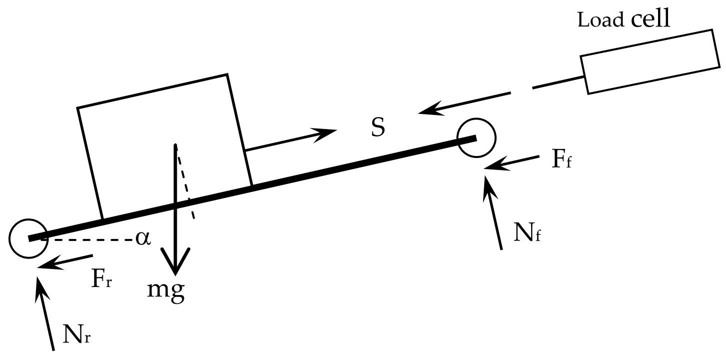

Figure 2. Free-body diagram of the experimental setup. Angle α is the inclination of the treadmill, S is the force registered in the load cell, m is the total mass of the roller ski and the load, g is the acceleration of gravity, N is normal force, F is rolling resistance and index r and f indicate the rear and forward positions of the forces.

Roller ski equilibrium in the direction of the incline, and perpendicular to it, produces the equations

$$F_r + F_f = S - mg \sin \alpha \tag{3}$$

and

$$N_r + N_f = N_{TOTAL} = mg \cos \alpha \tag{4}$$

With the coefficient of rolling resistance, μ_R, defined as the ratio of the total resisting force to the total normal force, the following relationship can be established

$$\mu_R(N_{TOTAL}, \alpha) = \frac{F_r + F_f}{N_r + N_f} = \frac{S - mg \sin \alpha}{mg \cos \alpha} \tag{5}$$

This relationship is used in all calculations of μ_R in the remainder of this thesis.

2.3.2 Warm-up study

To study whether a change in μ_R occurs during usage, measurements were taken during one hour of continuous running with 12 different roller skis (4 pairs of classical, 2 pairs of freestyle). A mass of 40.6 kg of lead was put on top of the roller skis in order to simulate the average weight of a person warming up the roller skis, changing between different techniques (double poling, diagonal stride etc.). The mean of μ_R was calculated for 60 seconds every tenth minute, starting with minute one and then normalized, i.e. all the values for each ski were divided by the value for the first minute of the test.

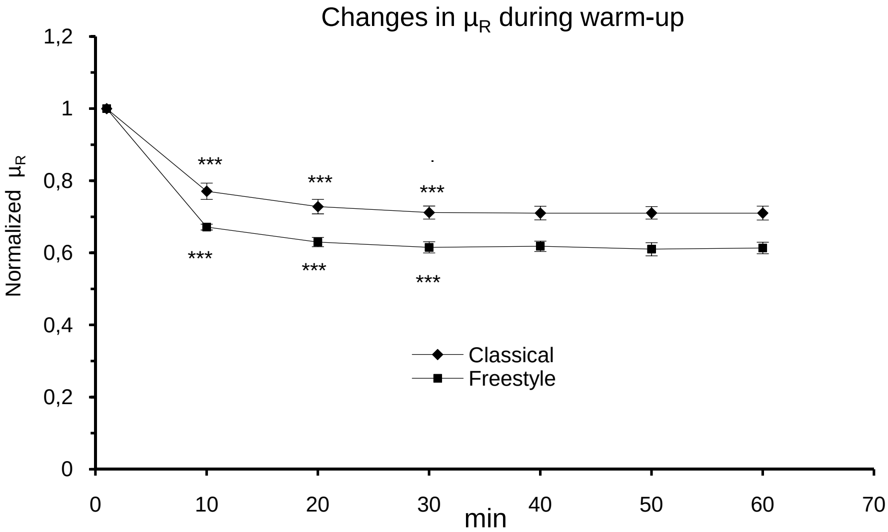

Figure 3. Normalized coefficient of rolling resistance, μ_R, during warm-up (mean ± *SD*). *** $p < 0.001$.

The results of the warm-up study showed a significant change in μ_R during the first 30 minutes of rolling, and for the following 30 minutes there was no significant change, see Fig. 3. The results also indicate differences in behaviour between the studied classical and freestyle roller skis. The rolling resistance coefficient of the freestyle roller skis decreased faster and to a lower value when compared to classical roller skis. As an average value, μ_R of the freestyle roller skis decreased to about 60-65%, while μ_R of the classical roller skis decreased to 70-75% of their initial value. This difference might be due to the different design of the tyres as described in section 2.1; classical roller skis have rather wide rubber tyres while freestyle roller skis have thinner, thermoplastic polyurethane tyres.

In addition, to see if the change in μ_R could be explained by a possible change in the temperature, T, of the roller ski's bearings, simultaneous measurements of μ_R and T were carried out with 6 classical roller skis with three different masses (20.6, 41.5 and 61.5 kg) put on top of the roller skis. The sensor from the thermometer was attached to the surface of the roller ski's rear, close to the wheel bolt.

For the three different loads, the relation between stabilized T and total normal force, N_{TOTAL}, under laboratory conditions was very close to a straight line, with the equation $T = 24.43 + 0.0234 \cdot N_{TOTAL}$. The comparison between T and μ_R changes showed that μ_R decreased as long as T increased and that a stabilized value of μ_R corresponded to a stabilized T (213N $r = -0.985$ $p = 0.000$, 418N $r = -0.983$ $p = 0.000$, 614N $r = -0.957$ $p = 0.001$), see Fig. 4.

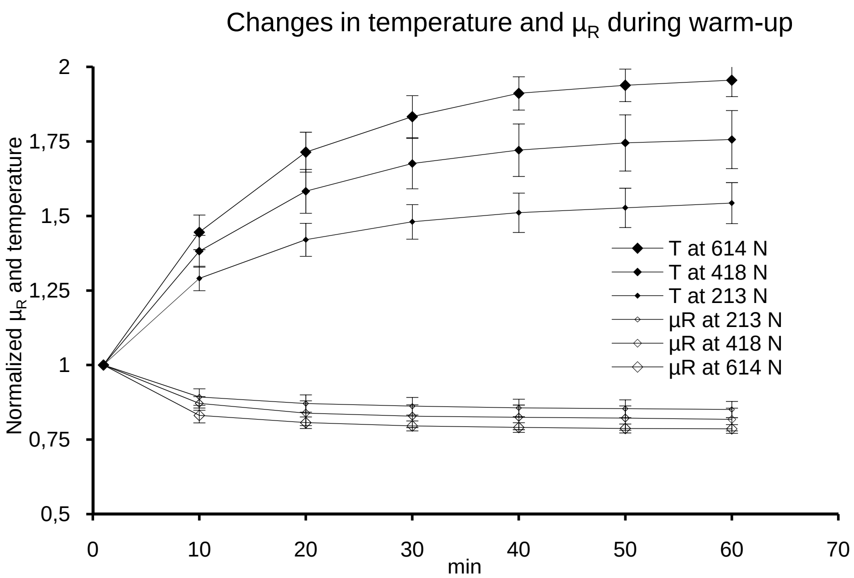

Figure 4. Normalized temperature, T, and coefficient of rolling resistance, μ_R, during warm-up with different normal forces. Data from classical roller skis (mean ± *SD*).

The study clearly showed that a proper warm-up period for the roller skis must precede testing with roller skis on a treadmill, otherwise the results of different physiological tests cannot be compared correctly. The study raised the idea that the warm-up of the roller skis on the treadmill could be replaced by controlled warming in a low-temperature oven. Based on the weight of the skier, the roller skis could be heated to the appropriate temperature and be ready to use at once.

2.3.3 Reproducibility study

The reproducibility of the rolling resistance measurement system was tested with a mass of 61.5 kg. Before starting to take measurements the individual roller ski was warmed up for 40 minutes due to the results of the warm-up study, see section 2.3.2. Two separate measurements were taken of the same load and between the measurements the treadmill was stopped and the mass and the roller ski were taken off the RRMS equipment. The roller ski and mass were then re-established and a measurement was reproduced using the same load. For each type of roller ski, classical and freestyle respectively, this paired procedure was repeated twelve times on different inclinations and velocities of the treadmill.

The results showed no significant difference between the paired measurements with either the classical (t = -1.539 p = 0.150, *SD* = 0.00050, *TEM* = 0.00037 %*TEM*= 2.27) or the freestyle roller ski (t = -1.575 p = 0.141, *SD* = 0.00080, *TEM* = 0.00058 %*TEM* = 4.84) and the *SD* and *TEM* was relatively small, especially for the classical roller ski. The higher *TEM* for the freestyle roller ski might be due to a different tyre design, as discussed above.

Another possible explanation might be the difference between the two protocols, where the freestyle roller ski protocol contained higher velocities than the classical roller ski protocol. At higher velocities greater vibrations in the treadmill and therefore in the RRMS fixture were observed.

2.3.4 The influence on μ_R of normal force, velocity and inclination

The coefficient of rolling resistance was also studied with 6 classical and 6 freestyle roller skis as a function of different normal forces on the roller ski, and velocities and inclinations of the treadmill. Before starting to take measurements the individual roller ski was warmed up for 40 minutes due to the results of the warm-up study, see section 2.3.2.

The study of the influence on μ_R of normal force produced a significant correlation between μ_R and normal force for both the classical (r = -0.978 p = 0.000) and freestyle roller skis (r = -0.967 p = 0.000). Within the studied range of normal forces μ_R decreased almost 35-45% for the classical and the freestyle roller skis respectively, see Fig. 5. With μ_R expressed as a linear function of N_{TOTAL} the following relationship was found for classical and freestyle roller skis within the range of N_{TOTAL} = 213 – 604 [N]:

Classical roller skis: $\mu_R = 0.038626 - 0.000027 \cdot N_{TOTAL}$

Freestyle roller skis: $\mu_R = 0.033572 - 0.000028 \cdot N_{TOTAL}$

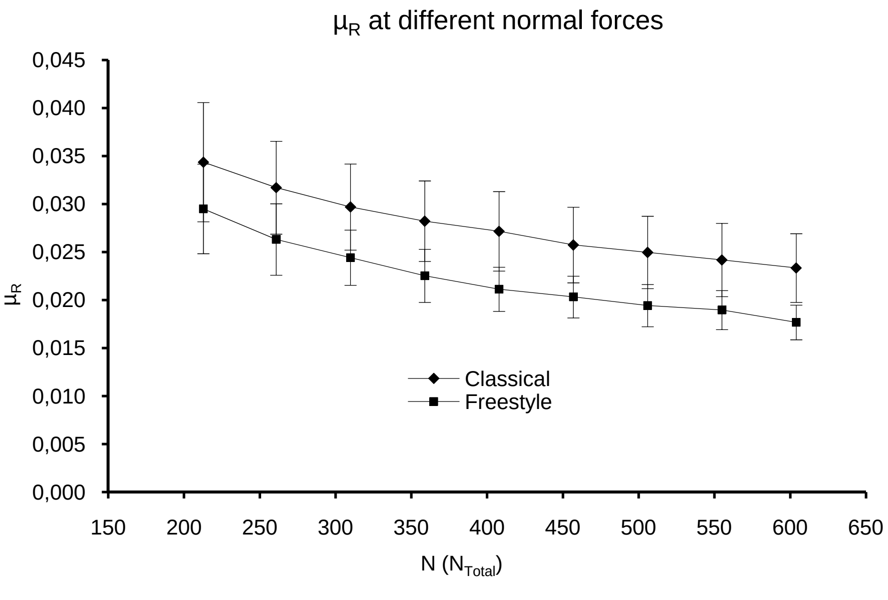

Figure 5. Coefficient of rolling resistance, μ_R, as a function of different normal forces on the roller skis (mean ± *SD*).

Different velocities of the treadmill only resulted in non significant changes of μ_R. Raising the velocity from 8 to 28 km/h resulted in a decrease of μ_R of less than 3% for the classical

(r = - 0.577 p = 0.230) and about 8% for the freestyle roller skis (r = - 0.611 p = 0.197), see Fig. 6. The similar study with a raised incline α from 0° - 9° produced a significant increase of μ_R of about 8% for classical (r = 0.889 p = 0.001) and a non significant increase of 2% (r =0.447 p = 0.195) for the freestyle roller skis, see Fig. 7.

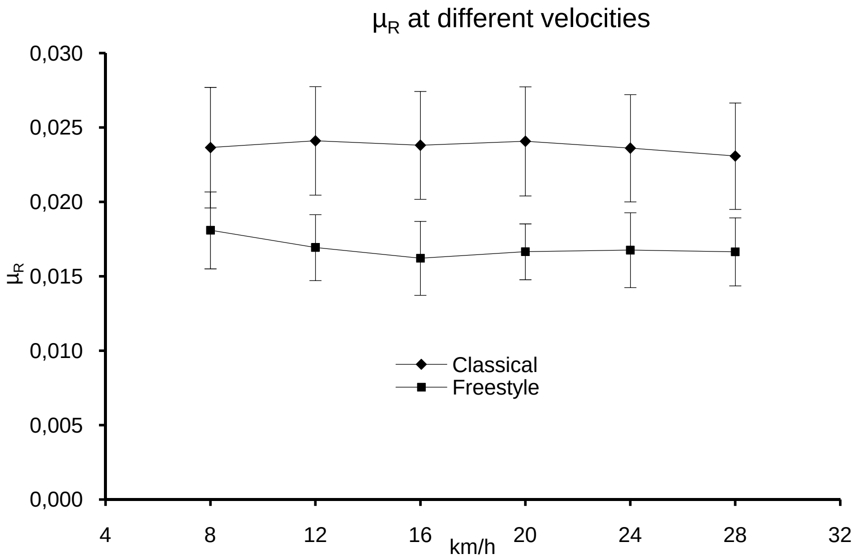

Figure 6. Coefficient of rolling resistance, μ_R, as a function of different velocities of the treadmill (mean ± *SD*).

In contrast to earlier studies (Hoffman *et al.* 1990b, 1994 and 1995, Millet *et al.* 1998), this study showed a clear negative correlation between normal force and μ_R. This phenomenon, together with the small positive correlation between inclination and μ_R (higher inclination means lower total normal force), is probably explained by a raised T in the roller bearings because of higher normal forces. Raised T in the bearings results in lower viscosity in the grease (Hamrock 2004), which results in lower rolling resistance. Increased velocity is also followed by increased heating in the roller bearing, resulting in lower μ_R. Greater changes in μ_R probably demand higher velocities.

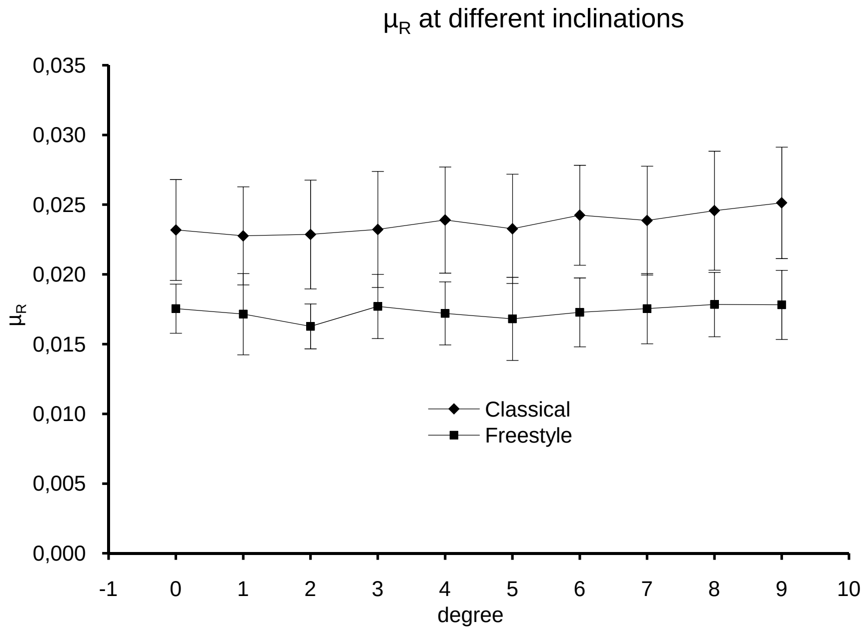

Figure 7. Coefficient of rolling resistance, μ_R, as a function of different inclinations of the treadmill (mean $\pm$ *SD*).

The relatively small, but significant, difference between the classical and the freestyle roller skis in μ_R as a function of inclination might be due to unequal changes of the individual normal forces, N_r and N_f, of the rear and forward wheels. While the classical roller skis had the centre of mass placed close to the rear wheel, see Fig. 1, the freestyle roller skis had the centre of mass closer to the middle of the roller skis, see section 2. Thus, when changing inclination, changes in individual normal forces were not the same for the two types of roller skis.

The error bars ($\pm$ 1*SD*) in Fig. 5, 6 and 7, gave a reflection of the variation in μ_R among the tested roller skis of the same model coming from the same manufacturer. The difference between the individual roller skis was of a magnitude up to μ_R 0.007 and μ_R 0.010 (28% and 34%) for the freestyle and classical roller skis, respectively. The differences follow the different rolling ages of the roller skis (roller ages not shown here). This is normal behaviour for roller bearings. They have a breaking in period when they are new, and during that period the rolling resistance slowly sinks as they grow older (SKF 2006).

2.4 Part II. Physiological responses to different rolling resistance coefficients

2.4.1 Subjects

A total of twenty elite athletes who compete in cross country skiing, biathlon and ski-orienteering at a national level volunteered to take part in physiological tests by roller skiing on a motorized treadmill by using the freestyle (Gear 3) or classical technique (diagonal stride). Characteristics of the participants are presented in Table 1.

Table 1. Characteristics of the participants. Freestyle study; n = 10 (five women and five men), classical study; n = 10 (four women and six men).

	Age [yr]	Bodymass [kg]	Height [cm]	$vO_{2\,max}$ [$mL \cdot kg \cdot min^{-1}$]	Pole length [% Height]
Freestyle					
Mean	25.9	66.99	174.9	60.3	90.2
SD	5.9	6.6	7.6	6.2	1.0
Classical					
Mean	26.0	72.8	176.5	63.1	84.6
SD	5.1	11.5	11.7	5.4	0.7

All the subjects had previous experience of roller skiing on a treadmill and were informed about the purpose and method of the upcoming study before giving their written consent to participate. Before each test occasion the subjects filled out a standard health form to declare their physical condition. The study was approved by the Ethics Committee of Umeå University, Umeå, Sweden.

2.4.2 Design

The subjects performed the same type of test on three different test occasions, and there was an average time of 6.4 days (4-12) between each occasion. Two of the test occasions, T1 and T2, were carried out on the same pair of roller skis and on the third occasion, T3, a different pair of roller skis was used. The order of the roller skis used was randomized, and the test subjects had no knowledge of the actual μ_R of the roller skis.

During the test period the subjects had been given instructions on standardised behaviour to follow, such as avoiding unfamiliar strenuous exercise, taking the same kind, intensity and amount of exercise throughout the whole period, and not to exercise the day before and the day of each test occasion. Food intake was to be normal for the subject and a meal was to be eaten 2-3 hours before each test occasion. Tests were also carried out at the same time of day on every test occasion for each subject.

On each test occasion, the subjects performed two submaximal workloads (~55% and ~75%$VO_{2\,MAX}$) of 10 min. each, followed by an incremental maximal test. The maximal tests were terminated when the subjects signalled it by taking out their mouthpiece. At this signal, the time to exhaustion, TTE, was noted.

Ratings of perceived exertion, RPE 6-20, (Borg 1998) were carried out for breathing, arms, and legs during the last minute on each submaximal workload and directly after exhaustion. Blood lactate, B-Hla, samples were taken during the last 30 s of each submaximal workload and one minute after exhaustion. During the last minute of the submaximal workloads the subjects were filmed with a 2-D video camera for analyses of cycle rates, CR, i.e. the number of cycles performed per minute. The length (distance) per cycle, CL, was also analysed by dividing the speed by CR. Results for oxygen uptake, VO_2, and heart rate, HR, were calculated as mean values from the last minute of the submaximal workload, and from 30 s of the adjacent highest values of the maximal test in order to determine maximal oxygen uptake, $VO_{2\,MAX}$, and maximal heart rate, HR_{MAX}.

In connection with the tests using freestyle technique (which took place before the classical) the freestyle roller skis were warmed up by a non-test person roller skiing on the treadmill for 30 minutes. Before the tests using the classical technique the classical roller skis were warmed up in a low-temperature oven for at least half an hour to a running temperature, T, corresponding to a certain normal force on the roller skis, $T = 24.43 + 0.0234 \cdot N_{TOTAL}$, see section 2.3.2.

2.4.3 Rolling resistance coefficients

Measurements to check the roller skis' μ_R were done on all three test occasions. The results showed that the two test occasions, T1 and T2, in the freestyle and classical part of the study, carried out on the same pair of freestyle and classical roller skis respectively, were accomplished with non significant differences in μ_R. Freestyle roller skis; T1 $\mu_R = 0.01772$, T2 $\mu_R = 0.01707$, T1 vs. T2 $p = 0.596$ and classical roller skis; T1 $\mu_R = 0.01969$, T2 $\mu_R = 0.01974$, T1 vs. T2 $p = 0.100$), see Fig. 8.

The test occasions carried out on a different pair of roller skis, T3, were accomplished with significantly different μ_R, which was 47% lower for the freestyle roller skis used in the freestyle part of the study, T3 $\mu_R = 0.00941$, T1 vs. T3 $p = 0.000$, T2 vs. T3 $p = 0.000$, and 50% higher for the classical roller skis used in the classical part of the study, T3 $\mu_R = 0.02949$, T1 vs. T3 $p = 0.000$, T2 vs. T3 $p = 0.000$, see Fig. 8.

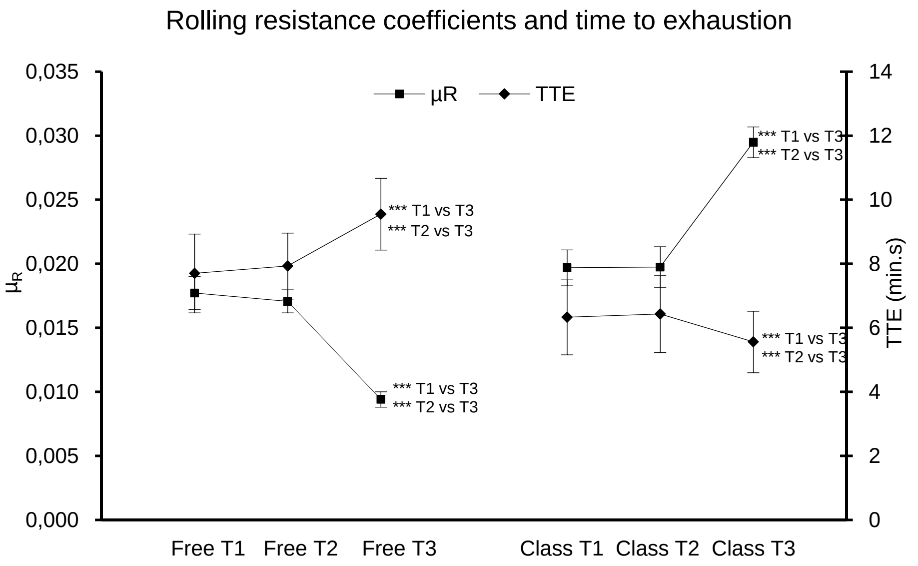

Figure 8. Rolling resistance coefficient (μ_R) for the freestyle (Free) and classical (Class) roller skis, and the time to exhaustion (TTE) from the incremental maximal tests, on the three test occasions (T1,T2,T3). Mean $\pm$ *SD*. *** $p < 0.001$.

These results for μ_R gave a good opportunity to study the reproducibility and significance of the athletes' performance between different test occasions with non significant variation in $\mu_{R,}$ putting this in relation to the results from the test occasion that was carried out with a significantly different μ_R.

A study to determine μ_R as a function of different normal forces, used for calculations of external power was completed using masses at 5 kg intervals within the range of 22.7-62.7 kg, corresponding to N_{TOTAL} 222.7-615.1 N. The study established the following linear dependence for the freestyle roller skis: T1 and T2 $\mu_R = -0.000023 \cdot N_{TOTAL} + 0.030438$ ($r = -0.970$, $p = 0.000$), T3 $\mu_R = -0.000012 \cdot N_{TOTAL} + 0.015830$ ($r = -0.990$ $p = 0.000$), and for the classical roller skis: T1 and T2 $\mu_R = -0.000026 \cdot N_{TOTAL} + 0.034790$ ($r = -0.987$, $p = 0.000$), T3 $\mu_R = -0.000016 \cdot N_{TOTAL} + 0.0352635$ ($r = -0.996$ $p = 0.000$).

2.4.4 External power ($P_{W\,EXT}$)

The external power, $P_{W\,EXT}$, from submaximal workloads, P_W, was calculated as the sum from elevating the transported mass against gravity, P, and overcoming the rolling resistance coefficient, $P\mu_R$, with the following equation:

$$P_W = P + P_{\mu R} = mg \cdot v(\sin\alpha + \mu_R \cdot mg\cos\alpha) \quad (6)$$

where v is the velocity of the treadmill expressed in $m \cdot s^{-1}$. Maximal external power output, $P_{W\,MAX}$, performed during incremental maximal tests was calculated using a method used in bicycle research (Padilla *et al.* 2000) (in Padilla *et al.* Wmax = *Wf* + [(t/240)x35]) with the following equation:

$$P_{W\max} = P_W + P_R \cdot (t/60) \quad (7)$$

where P_R is the relative power output difference between the last two P_W, t is the time the last P_W was maintained (s) and 60 s is the duration of each P_W.

2.4.5 The influence of μ_R on steady state exercises

A comparison between the two test occasions carried out on the same pair of roller skis with no significant difference in μ_R, T1 vs. T2, resulted in non significant differences for P_W, VO_2, HR and B-Hla, see Fig. 9-12, and for CL, RPE breathing, arms and legs (results not shown here). Only CR, in the first submaximal workload in the freestyle part of the study, showed a significantly changed result, see Fig. 13.

The use of different pairs of roller skis with 47% lower and 50% higher μ_R, on the third, T3, freestyle and classical test occasions respectively, resulted mostly in significantly changed P_W, VO_2, HR and B-Hla at the submaximal workloads.

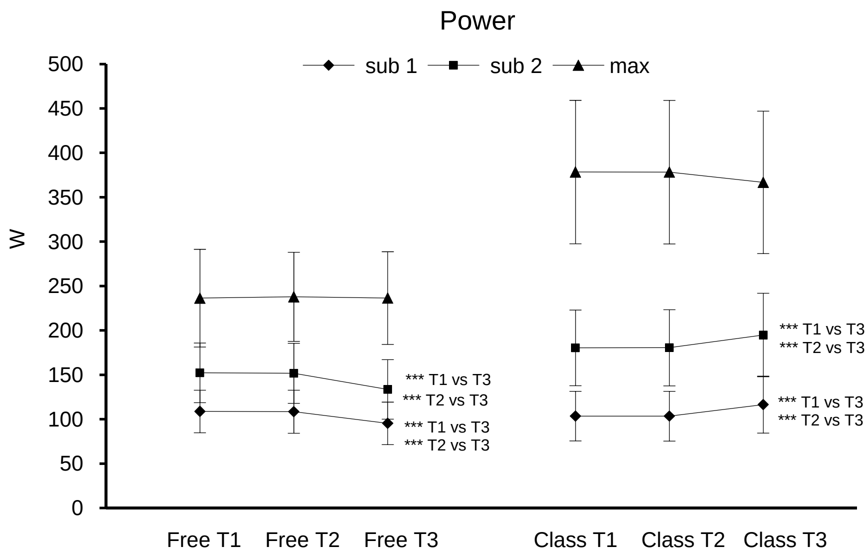

Figure 9. Power (P_W) from two submaximal workloads (sub 1, sub 2) and from an incremental maximal test (max) on three test occasions (T1,T2,T3) using freestyle (Free) and classical (Class) techniques on roller skis. Mean ± *SD*. *** $p < 0.001$.

P_W was significantly decreased, by an average of 12.2%, in both submaximal workloads in the freestyle part of the study and significantly increased by 12.6% and 8.0% in the first and second submaximal workloads respectively, in the classical part of the study, see Fig. 9.

VO_2 was significantly decreased by 7.4-9.4% in the freestyle part of the study and significantly increased by 5.4-6.8% in the classical part of the study, see Fig. 10. This result clearly shows that control of the roller skis' μ_R must be carried out in connection with tests of comparisons of submaximal oxygen uptake from steady state workloads, otherwise results of, for example, work economy cannot be accurately compared.

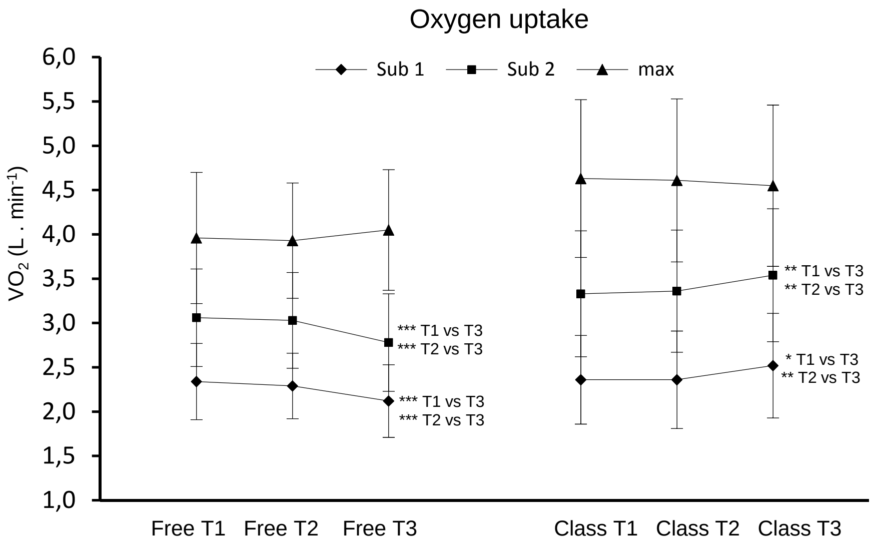

Figure 10. Oxygen uptake (VO_2) from two submaximal workloads (sub 1, sub 2) and from an incremental maximal test (max) on three test occasions (T1,T2,T3) using freestyle (Free) and classical (Class) techniques on roller skis. Mean ± *SD*. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

HR was significantly changed in the second submaximal workloads, except for T2 vs. T3 in the classical part of the study, while there were non significant differences in the first submaximal workloads, except for T2 vs. T3 in the freestyle part of the study, which was significantly changed, see Fig 11. HR decreased by 5.9-8.3% in the freestyle part of the study and increased by 3.2-6.4% in the classical part of the study. Åstrand *et al.* (1986) mention that emotional factors can affect heart rate during light and moderate intensity exercise, and during repeated maximal exercise the heart rate is, however, remarkably similar under various conditions. Also, a variation in heart rate at a given oxygen uptake at rest and during submaximal exercise often produces a change in stroke volume so that cardiac output is maintained at an appropriate level.

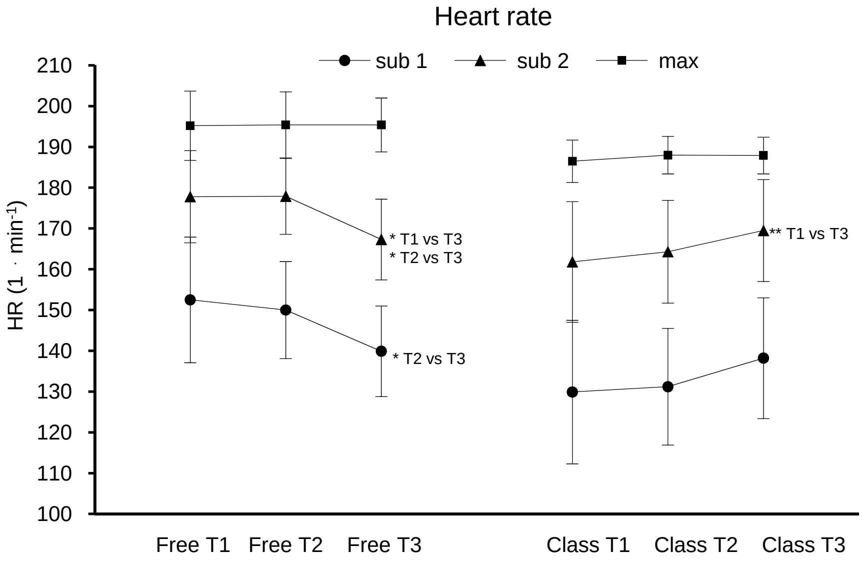

Figure 11. Heart rates (HR) from two submaximal workloads (sub 1, sub 2) and from an incremental maximal test (max) on three test occasions (T1,T2,T3) using freestyle (Free) and classical (Class) techniques on roller skis. Mean $\pm$ *SD*. * $p < 0.05$, ** $p < 0.01$.

B-Hla concentrations were significantly changed in the second submaximal workloads, while differences in the first submaximal workloads were mostly non significant, see Fig. 12. B-Hla decreased by 20.3-38.8% in the freestyle part of the study and increased by 14.6-46.6% in the classical part of the study. This partially unequal result for B-Hla between the freestyle and classical part of the study, and between the two submaximal workloads, can be explained by differences in $\%VO_{2\ MAX}$ and how lactate responds to increased workload. The classical part of the study had an easier first workload than the freestyle part of the study (~51%$VO_{2\ MAX}$ and ~59%$VO_{2\ MAX}$, respectively). Consequently, the B-Hla concentration was lower in the first submaximal workload in the classical than in the freestyle part of the study. The B-Hla response curve does not have a linear increase, in contrast to HR and VO_2, with a linear increase in exercise (Gore 2000, McArdle *et al.* 2001). For elite athletes performing incremental light to moderate exercise there may be a baseline where lactate does not increase significantly with an increase in workload. During harder exercise, the ratio of increased lactate to increased P_W changes quickly due to oxygen deficiency. Thus B-Hla is more sensitive to a change in μ_R during harder exercise, as can be seen in Fig 12. At an intensity of ~75% of $VO_{2\ MAX}$, on the second submaximal workloads, this study showed that B-Hla changed ~40% to a ~50% decrease or increase in μ_R.

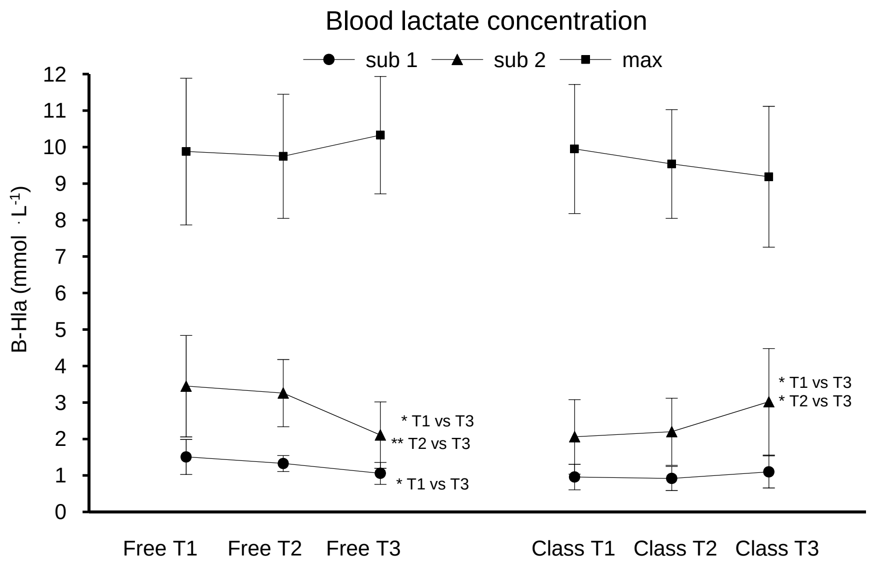

Figure 12. Blood lactate (B-Hla) concentrations from two submaximal workloads (sub 1, sub2) and after an incremental maximal test (max) on three test occasions (T1,T2,T3) using freestyle (Free) and classical (Class) techniques on roller skis. Mean ± *SD*. * $p < 0.05$, ** $p < 0.01$.

In most cases RPE resulted in non significant differences between the three test occasions (results on RPE not presented here). Only RPE for breathing and arms (only T2 vs. T3), in the second submaximal workload in the classical part of the study, showed a significant change between test occasions with significantly different μ_R. RPE for breathing decreased by 3.8-8.7% in the freestyle part of the study and increased by 0.0-8.4% in the classical part of the study. RPE for arms decreased by 4.8-8.3% in the freestyle part of the study and increased by 2.3-7.1% in the classical part of the study. RPE for legs decreased by 1.0-4.8% in the freestyle part of the study and increased by 0.7-5.1% in the classical part of the study.

The earlier interpretation, that lactate is the cause of muscle fatigue, has recently become controversial (Allen *et al.* 2008). However, it is well known that high intensity exercise (and high energy requirements) is partially generated by anaerobic metabolism, which leads to lactate accumulation with *a relation* to muscle fatigue (McArdle *et al.* 2001). In this study the significant change of 35-46% for B-Hla in the second submaximal workloads, due to an increased anaerobic metabolism, was in most cases not large enough for the participants to rate a significantly changed muscle fatigue.

In most cases CR and CL were non significantly different between the three test occasions (results for CL are not presented here). A significant difference was found for CR, in the first submaximal workload in the freestyle part of the study, between the two test occasions with non significant difference in μ_R, see Fig. 13. Between the test occasions with significantly different μ_R, only T1 vs T3 in the second submaximal workload in the freestyle part of the study resulted in significant changes for CR and CL. In the first submaximal workload, in the freestyle part of the study, CR on average both decreased by 4.7% and increased by 1.3% and CL both decreased by 0.8% and increased by 5.4%. In the classical part of the study CR increased on average by 0.3-3.0% and CL decreased by 0.3-2.8%.

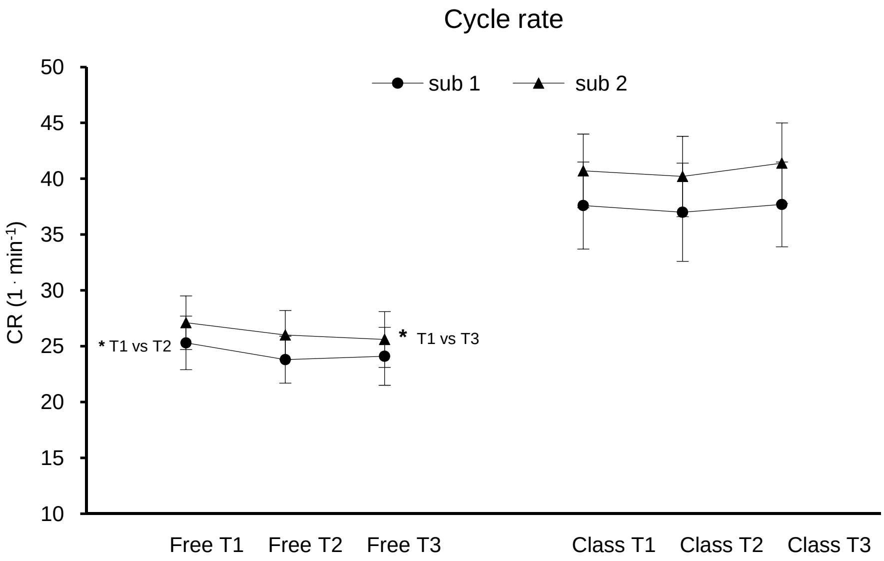

Figure 13. Cycle rates (CR) from two submaximal workloads (sub 1, sub 2) on three test occasions (T1,T2,T3) using freestyle (Free) and classical (Class) techniques on roller skis. Mean ± *SD*. * $p < 0.05$.

There are three possibilities for adaptation to a change in μ_R (or a change in velocity and/or inclination of the treadmill); to change CR or CL independently or CR and CL together. The results of this study showed that the latter alternative was chosen by the athletes, and of course a change in μ_R is of smaller importance when distributed over two variables rather than a single variable. A comparison between the first and second submaximal workload for CR vs. VO_2 and P_W shows that an increase in VO_2 of ~32% and ~40% and in P_W by ~42% and ~75%, for the freestyle and classical part of the study respectively, only increases CR by ~8%. Thus the significant change in P_W of 8-12% within the same workload, due to the significant change in μ_R, obviously had little influence on CR.

2.4.6 The influence of μ_R on incremental maximal tests

Between the incremental maximal tests that tested freestyle and classical technique roller skiing with non significant differences in μ_R, T1 vs. T2, there were non significant differences in TTE, $P_{W\ MAX}$, $VO_{2\ MAX}$, $HR_{\ MAX}$, and B-Hla, see Fig. 8-12, and for RPE breathing, RPE arms and RPE legs (results for RPE not shown here).

The use of different pairs of roller skis with 47% lower and 50% higher μ_R, on the third freestyle and classical test occasions, T3, respectively, resulted in a significantly changed TTE on the incremental maximal tests, see Fig. 8. TTE increased by 20.4-24.0% and decreased by 12.2-13.5% in the freestyle and classical part of the study, respectively. This result clearly shows that TTE is greatly influenced by changes in μ_R and that whenever this variable is evaluated it is important to control the roller skis' μ_R.

This change in TTE occurred without significant changes in $P_{W\ MAX}$, $VO_{2\ MAX}$, $HR_{\ MAX}$ and B-Hla, see Fig. 9-12, and RPE except for the arms (T2 vs. T3) in the classical part of the study. Thus $P_{W\ MAX}$, when changing μ_R and the power for overcoming the rolling resistance, $P\mu_R$, is almost fully compensated by a change in power from elevating the transported mass against gravity, P. It is perhaps not surprising that μ_R had very little influence on $VO_{2\ MAX,}$ since a non significant change in $VO_{2\ MAX}$ with protocols of different duration and design has been reported in other situations (Roffey *et al.* 2007, Zhang *et al.* 1991).

It is difficult to compare the results of this study with similar studies since this study was carried out in stationary conditions, while a comparative study measured the roller skis' μ_R on a treadmill using a different method and with the physiological measurements carried out outdoors on asphalt, i.e. on a different surface with an unknown friction between the roller skis and the surface (Hoffman *et al.* 1998). Outdoor measurements also imply air resistance and often a varying ambient and surface temperature. The results presented in section 2.3.2. showed that μ_R is temperature dependent. In Hoffman *et al.* (1998) the ambient temperature ranged from 15.2 to 36.8°C during testing. Nevertheless, the results in this study showed a change in VO_2 of ~7% for a 50% change in μ_R, which is quite similar to that reported by Hoffman *et al.* (1998) (13% to a 100% increase in μ_R), while HR in this study showed a change of ~6%, which is more than double the comparative (5% to a 100% increase in μ_R). The external power output in this study was changed by 8-12% due to the 50% change in μ_R, while Hoffman *et al.* (1998) presented a change of 17% to a 100% increase in μ_R.

2.5 Part III. Work economy during treadmill roller skiing

2.5.1 Subjects

A total of 84 subjects volunteered to take part in physiological tests of work economy by roller skiing on a motorized treadmill using the freestyle technique, Gear 3, or the classical technique diagonal stride, DIA. Within each technique they were arranged in five different groups according to skill, age and gender: Men amateur cross country skiers, MA, men and women elite seniors, MS and WS respectively, who compete in cross country skiing and biathlon at a high national and international level, and men and women juniors, MJ and WJ respectively, aiming for an elite career. Characteristics of the participants are presented in Table 2. All the subjects had previous experience of roller skiing on a treadmill. The study was approved by the Ethics Committee of Umeå University, Umeå, Sweden.

Table 2. Characteristics of the participants in the different testing groups (Mean ± *SD*), using freestyle technique Gear 3 and classical technique diagonal stride (DIA). n = number of participants in the different groups.

	MA	MS	MJ	WS	WJ
Freestyle Gear 3 n =	6	5	7	7	7
Age [yr]	38.7 ± 11.3	26.6 ± 2.7	18.6 ± 1.3	25.1 ± 6.2	18.0 ± 1.5
Body mass [kg]	79.1 ± 11.6	78.0 ± 4.1	72.0 ± 8.6	62.3 ± 4.5	62.1 ± 4.7
Equipment mass [kg]	3.3 ± 0.1	3.2 ± 0.0	3.2 ± 0.1	3.0 ± 0.1	3.0 ± 0.1
$vO_{2\,max}$ [$mL \cdot kg^{-1} \cdot min^{-1}$]	51.7 ± 4.8	66.4 ± 3.9	64.4 ± 1.8	56.9 ± 8.5	52.6 ± 1.9
Classical DIA n =	13	10	9	10	10
Age [yr]	36.8 ± 10.4	22.0 ± 2.3	17.6 ± 1.3	21.9 ± 1.9	17.9 ± 1.0
Body mass [kg]	82.3 ± 9.0	76.4 ± 6.6	73.6 ± 8.9	62.0 ± 4.5	62.9 ± 6.5
Equipment mass [kg]	3.4 ± 0.1	3.4 ± 0.1	3.4 ± 0.1	3.2 ± 0.0	3.2 ± 0.0
$vO_{2\,max}$ [$mL \cdot kg^{-1} \cdot min^{-1}$]	53.3 ± 4.0	68.5 ± 2.2	64.2 ± 4.2	59.7 ± 1.5	52.9 ± 4.9

2.5.2 Design

Before the tests, the subjects were given instructions on standardised behaviour to follow, such as avoiding unfamiliar strenuous exercise the week before the test and not to exercise the day before and the day of the test. Food intake was to be normal for the subject and a meal was to be eaten 2-3 hours before the test was conducted.

The subjects performed 4-6 submaximal workloads of 4 minutes each. The number of workloads performed was limited by the subject's skill and maximal aerobic capacity, and the final workload was settled when the respiratory quotient, RQ, reached between 1.05-1.10. The common workload for analyses was predetermined to be beneath a mean per group B-Hla of 4 mmol $\cdot$ L^{-1} (OBLA), due to minimizing the involvement of anaerobic energy. After the final submaximal workload the participants performed an incremental maximal test with the aim of characterizing their $vO_{2\,MAX}$. The results for VO_2, HR and RQ were calculated as described in section 2.4.2. The vO_2 and $vO_{2\ MAX}$ was calculated from the sum of the total mass of the equipment (roller skis, ski-boots and ski-poles) and the body mass. Before the tests the roller skis were warmed up in a low-temperature oven as described in section 2.3.2.

2.5.3 Rolling resistance coefficients and external power

A study to determine μ_R as a function of different normal forces, used for calculations of external power, $P_{W\ EXT}$, was completed. The study established the following relationships and correlations for the freestyle roller skis; $\mu_R = -0.000023 \cdot N_{TOTAL} + 0.030438$ (r = -0.970, p = 0.000), and for the classical roller skis; $\mu_R = -0.000012 \cdot N_{TOTAL} + 0.026558$ (r = -0.932, p = 0.000).

The results of external power per kg, $p_{W\ EXT}$, presented in Fig. 13., showed significant differences between the two genders except for the MJ in the freestyle part of the study; Freestyle: MA and WS (p = 0.003), MA and WJ (p = 0.002), MS and WS (p = 0.010), MS and WJ (p = 0.009). Classical; MA and WS (p = 0.000), MA and WJ (p = 0.000), MS and WS (p = 0.001), MS and WJ (p = 0.002), MJ and WS (p = 0.021), MJ and WJ (p = 0.037).

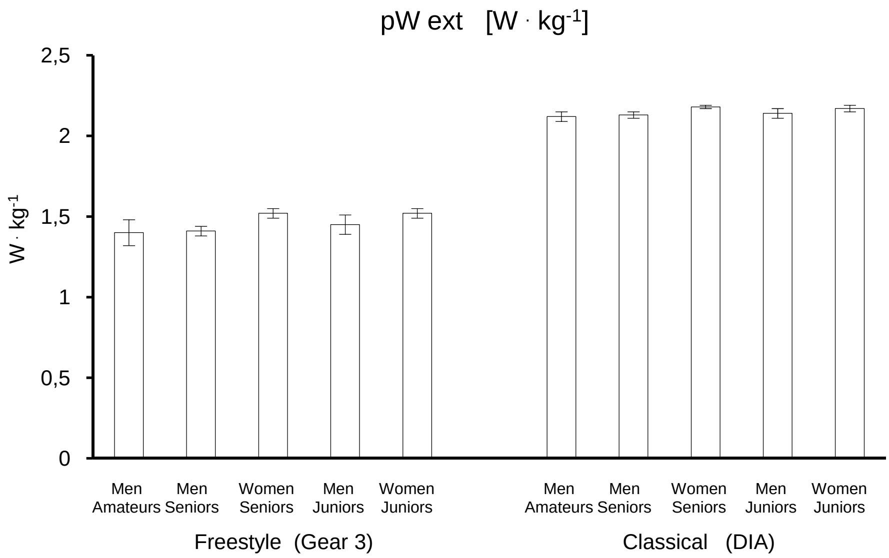

Figure 13. Results expressed as power per kg for the different testing groups using freestyle and classical roller skis, respectively. Mean $\pm$ *SD*.

The significant differences that were found were due to the differences in power for overcoming the roller skis' rolling resistance, $P\mu_R$, which in turn varied as a function of different body masses (normal forces). The lighter female testing groups were roller skiing with a relatively heavier rolling resistance coefficient, compared to the heavier testing groups of male participants. Thus, this additionally emphasizes, together with the significant influence μ_R has on VO_2 (section 2.4.5), the importance of knowing the roller skis' μ_R and the $p_{W\ EXT}$ in order to allow correct comparisons of work economy during steady state exercises.

2.5.4 Internal power

The RQ is the ratio of the CO_2 produced to the O_2 consumed. Due to the different chemical composition of fats and carbohydrates, fat catabolism requires more oxygen than the carbon dioxide production (McArdle *et al.* 2001). The distribution between fats and carbohydrates changes in accordance with the degree of activity. Thus, the RQ also changes and each litre of oxygen consumed liberates the following calorie, K_{CAL}, expenditure for a RQ between 0.707-1.00:

$$P_{GROSS}\ [K_{CAL} \cdot \min^{-1}] = (1.232 \cdot RQ + 3.8149) \cdot VO_2[L \cdot \min^{-1}] \tag{8}$$

where the gross energy expenditure, P_{GROSS}, is the sum of the resting metabolic rate, P_{RMR}, and the true requirement of the exercise, P_{NET}, without P_{RMR} (McArdle *et al.* 2001). Finally, to prepare for calculations of external and internal power efficiency ratio, the internal power, $P_{W\ INT}$, was converted into units of watts [W] by dividing the P_{GROSS} by 0.01433.

2.5.5 Power and mechanical efficiency

The only significant difference found in power efficiency, $P_{W\ EXT}/VO_2$, was between the MA vs. the other four groups, except vs. MJ in the part of the study that tested DIA, where no significant difference was found, see Fig. 14.

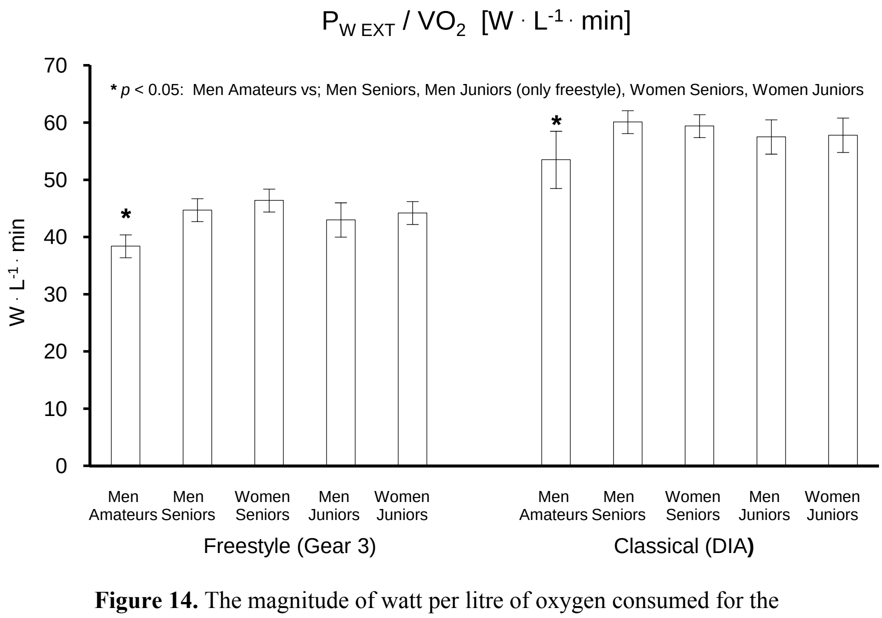

Figure 14. The magnitude of watt per litre of oxygen consumed for the different testing groups using freestyle and classical technique, respectively. Mean ± *SD*.

A similar result was found for mechanical efficiency, $P_{W\ EXT}/P_{W\ INT}$, except for a significant difference found between MA vs. MJ in the DIA part of the study, see Fig. 15.

Thus, in either of the two ways of expressing work economy, the difference of 1-8% between the four groups of elite competitors showed no significant difference, i.e. there was non significant difference between the genders, which agrees with results on DIA found by McDougall *et al.* (1979) and Hoffman *et al.* (1995), and between the juniors vs. the senior elite athletes. It was only the group of MA who showed a significantly different work economy, by 7-18%, among the five studied groups.

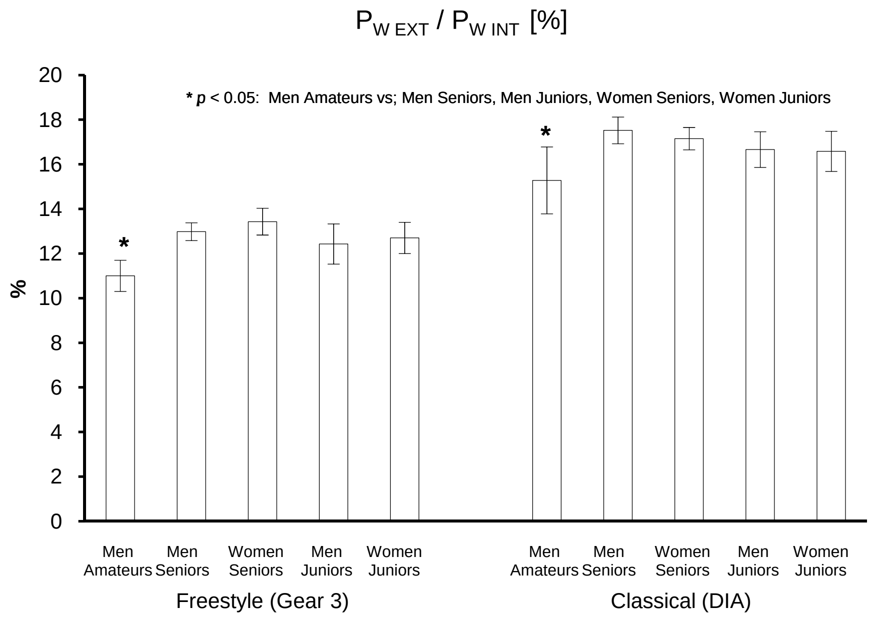

Figure 15. The external and internal power efficiency ratio for the different testing groups using freestyle and classical technique, respectively. Mean ± *SD*.

The difference in significance result, for MA vs. MJ, between $P_{W\ EXT}/VO_2$ and $P_{W\ EXT}/P_{W\ INT}$ was due to a significantly higher RQ for the MA in DIA (results not presented here). A low RQ is particularly important in competitions with longer durations, since it shows the advantage of sparing carbohydrates and instead using more fats as fuel. The $P_{W\ EXT}/P_{W\ INT}$ is therefore suitable for comparison between subjects and groups when the calorie expenditure is of interest and when studying mechanical efficiency between different sports and core techniques. However, at a given workload, the RQ is usually different between subjects and groups if large differences exist in maximal aerobic capacity, as in the present study. If such conditions exist, and the calorie expenditure is not of interest, the most adequate way of studying work economy is probably the external power in direct relation to the oxygen consumption.

2.6 Study limitations

The results in Part I showed some differences in behaviour between the classical and freestyle roller skis. However, the overall findings were similar for both types of roller skis, despite the differences in their construction, i.e. the classical roller skis were equipped with rather wide rubber tyres, while the freestyle roller skis had thinner, thermoplastic polyurethane tyres. Even though there were similar results for the classical and freestyle roller skis despite their differences in construction, it cannot be established that the results in this study can be applied to all types of roller skis, since this study did not investigate the rolling resistance of roller skis from more than one manufacturer.

Another source of uncertainty is the side forces on the wheels that occur during freestyle roller skiing. How these forces affect rolling resistance is not examined in this study. Differences in construction and side forces will both have some influence on the rolling resistance part of the power calculations.

The rolling resistance measurements were made using specific equipment, independent of human influence and with a "static" normal force, in contrast to the more "dynamic" normal force acting on the wheels during human roller skiing. In the experiments in Parts II and III it was assumed that a particular value of μ_R, and a significant or non significant change in μ_R, established in the apparatus, likewise exist during human roller skiing.

The Part III of this thesis was based on a contribution to a conference. Due to the restrictions set by the conference board, this part is more limited in several fields than Parts I and II. However, the intention is to further develop it into an article on the topic by adding more participants in some of the studied groups, and by investigating more workloads between the four groups of elite competitors, for comparisons closer to their $VO_{2\,MAX}$. Also, to add groups together, MS+MJ vs. WS+WJ and MS+WS vs. MJ+WJ, for further comparisons of work economy between the two genders and as a function of age, respectively.

2.7 Conclusions

In conclusion, this thesis has highlighted four key results from the experiments carried out using roller skis on the treadmill in stationary conditions. They can be explained as follows:

1. During a warm-up period of 30 min., freestyle and classical roller skis' μ_R significantly decreased to 60-75% of its initial value. For another 30 minutes of rolling no significant change was found. Thus, the results from the warm-up study showed that a proper warm-up of the roller skis must proceed physiological testing, otherwise results cannot be accurately compared.
2. The study of the influence on μ_R of normal force, velocity and inclination showed that μ_R was strongly influenced by normal force, while the different velocities and inclinations of the treadmill had little influence on μ_R. Within a range of normal forces, N_{TOTAL} = 213 – 604 N, μ_R decreased almost 35-45% for the classical and the freestyle roller skis respectively. Also, the variation in μ_R between individual roller skis of the same model from the same manufacturer were of a magnitude up to 28 and 34% for the tested freestyle and classical roller skis, respectively.
3. The study of the effects of a ~50% change in μ_R on physiological variables on *submaximal steady state exercises* in most cases resulted in significant changes; P_W of 8-12%, VO_2 of 5-9%, HR of 3-8% and B-Hla 14-46%, while there were mostly non significant and small changes to CR, CL and RPE. The study showed a tendency for some of the variables to be more influenced by changes in μ_R during harder rather than lighter submaximal steady state exercise. The *incremental maximal tests* showed that TTE was significantly changed by 12-24% and this occurred without a significantly changed $P_{W\ MAX}$, $VO_{2\ MAX}$, HR_{MAX} and B-Hla, and that the influence on RPE was non significant or small.
4. The study of work economy showed that the group of male amateurs had a significantly poorer work economy of 7-18%, compared to the junior and senior men and women elite cross-country skiers. Between the latter four groups there were non significant differences of ~1-8%. The results also showed that $p_{W\ EXT}$ was significantly different between some of the tested groups, due to differences in $P\mu_R$.

Thus the results of this thesis confirm the importance of knowing the roller skis' rolling resistance in order to allow correct comparisons between the results of different test occasions, particularly at submaximal steady state workloads.

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