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PHYSIOLOGICAL AND BIOMECHANICAL FACTORS DETERMINING CROSS-COUNTRY SKIING PERFORMANCE

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ABSTRACT

Cross-country (c.c.) skiing is a complex sport discipline from both physiological and biomechanical perspectives, with varying course topographies that require different proportions of the involved sub-techniques to be utilised. A relatively new event in c.c. skiing is the sprint race, involving four separate heats, each lasting 2-4 min, with diverse demands from distance races associated with longer durations. Therefore, the overall aim of the current thesis has been to examine the biomechanical and physiological factors associated with sprint c.c. skiing performance through novel measurements conducted both in the field (*Studies I-III*) and the laboratory (*Studies IV* and *V*).

In *Study I* sprint skiing velocities and sub-techniques were analysed with a differential global navigation satellite system in combination with video recording. In *Studies II* and *III* the effects of an increasing velocity (moderate, high and maximal) on the biomechanics of uphill classical skiing with the diagonal stride (DS) (*Study II*) and herringbone (HB) (*Study III*) sub-techniques were examined.

In *Study I* the skiers completed the 1,425 m (2 x 712 m) sprint time trial (STT) in 207 s, at an average velocity of 24.8 km/h, with multiple technique transitions (range: 21-34) between skiing techniques (i.e., the different gears [G2-7]). A pacing strategy involving a fast start followed by a gradual slowing down (i.e., positive pacing) was employed as indicated by the 2.9% faster first than second lap. The slower second lap was primarily related to a slower (12.9%) uphill velocity with a shift from G3 towards a greater use of G2. The maximal oxygen uptake ($\dot{V}O_{2max}$) was related to the ability to maintain uphill skiing velocity and the fastest skiers used G3 to a greater extent than G2. In addition, maximal speed over short distances (50 and 20 m) with the G3 and double poling (DP) sub-techniques exerted an important impact on STT performance.

Study II demonstrated that during uphill skiing (7.5°) with DS, skiers increased cycle rate and cycle length from moderate to high velocity, while cycle rate increased and cycle length decreased at maximal velocity. Absolute poling, gliding and kick times became gradually shorter with an elevated velocity. The rate of pole and leg force development increased with elevated velocity and the development of leg force in the normal direction was substantially faster during skiing on snow than previous findings for roller skiing, although the peak force was similar in both cases. The fastest skiers applied greater peak leg forces over shorter durations.

S*tudy III* revealed that when employing the HB technique on a steep uphill slope (15°), the skiers positioned their skis laterally ("V" between 25 to 30°) and planted their poles at a slight lateral angle (8 to 12°), with most of the propulsive force being exerted on the inside forefoot. Of the total propulsive force, 77% was generated by the legs. The cycle rate increased across all three velocities (from 1.20 to 1.60 Hz), while cycle length only increased from moderate to high velocity (from 2.0 to 2.3 m). Finally, the magnitude and rate of leg force generation are important determinants of both DS and HB skiing performance, although the rate is more important in connection with DS, since this sub-technique involves gliding.

In *Studies IV* and *V* skiers performed pre-tests for determination of gross efficiency (GE), $\dot{V}O_{2max}$, and V_{max} on a treadmill. The main performance test involved four self-paced STTs on a treadmill over a 1,300-m simulated course including three flat (1°) DP sections interspersed with two uphill (7°) DS sections.

The modified GE method for estimating anaerobic energy production during skiing on varying terrain employed in *Study IV* revealed that the relative aerobic and anaerobic energy contributions were 82% and 18%, respectively, during the 232 s of skiing, with an accumulated oxygen (O_2) deficit of 45 mL/kg. The STT performance time was largely explained by the GE (53%), followed by $\dot{V}O_2$ (30%) and O_2 deficit (15%). Therefore, training strategies designed to reduce energetic cost and improve GE should be examined in greater detail.

In *Study V* metabolic responses and pacing strategies during the four successive STTs were investigated. The first and the last trials were the fastest (both 228 s) and were associated with both a substantially larger and a more rapid anaerobic energy supply, while the average $\dot{V}O_2$ during all four STTs was similar. The individual variation in STT performance was explained primarily (69%) by the variation in O_2 deficit. Furthermore, positive pacing was employed throughout all the STTs, but the pacing strategy became more even after the first trial. In addition, considerably higher (~ 30%) metabolic rates were generated on the uphill than on the flat sections of the course, reflecting an irregular production of anaerobic energy. Altogether, a fast start appears important for STT performance and high work rates during uphill skiing may exert a more pronounced impact on skiing performance outdoors, due to the reduction in velocity fluctuations and thereby overall air-drag.

Keywords: cycle characteristics, energy cost, energy yield, incline, joint angles, kinematics, kinetics, mechanics, Nordic skiing, oxygen deficit, oxygen demand, technique transitions, total metabolic rate.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Längdskidåkning är en komplex idrott från både ett fysiologiskt och biomekaniskt perspektiv på grund av den stora variationen mellan olika banprofiler där flertalet deltekniker involveras i olika grad samt att arbetstiden varierar stort mellan olika tävlingsdistanser. Syftet med denna avhandling var att undersöka hur biomekaniska och fysiologiska faktorer är associerade till prestationsförmågan inom sprintskidåkning genom tester vid skidåkning utomhus på snö (*Studie I-III*) och vid rullskidåkning inomhus på rullband (*Studie IV* och *V*).

I *Studie I* undersöktes fartstrategier och teknikval/växelval (Vx2-7) vid sprintskidåkning med ett avancerat positioneringssystem (d-GNSS) som kombinerades med videoanalys. Ett individuellt sprintlopp på 1425 m (2 x 712 m) genomfördes på 3:27 min:s (24.8 km/h) och under loppet genomförde skidåkarna i genomsnitt 28 växlingar mellan de olika delteknikerna. En positiv farthållningsstrategi användes av skidåkarna (d.v.s. en snabb start med en gradvis sänkning av åkhastigheten) med ett något snabbare (3 %) första varv. Den långsammare åkhastigheten under det andra varvet var huvudsakligen relaterat till en långsammare (12.9 %) åkning uppför där skidåkarna använde Vx2 i större utsträckning gentemot Vx3. Vidare var den maximala syreupptagningsförmågan positivt relaterad till skidåkarens förmåga att bibehålla hastigheten i uppförsbackarna där en större användning av Vx3 jämfört med Vx2 var positivt kopplat till prestation. En hög maximal fartförmåga i Vx3 (50 m sprinttest) visade sig också vara en betydelsefull faktor för ett snabbt sprintlopp.

I *Studie II* och *III* genomfördes den första biomekaniska analysen av diagonal- och saxningsteknik vid skidåkning uppför (7,5° backlutning vid diagonal och 15° vid saxning) med tre olika relativa åkhastigheter (medel, hög och maximal). Vid diagonalskidåkning (*Studie II*) ökade skidåkarna hastigheten från medel till hög arbetsintensitet med en parallell ökning av både rörelsefrekvens (åkcykler/sekund) och åkcykellängd (m), men från hög upp till maximal åkhastighet ökades rörelsefrekvensen markant medan åkcykellängden minskade något. De skidåkare som uppnådde de högsta maximala åkhastigheterna utvecklade en större kraft med benen som utvecklades över en kortare tid och uppnådde samtidigt en högre rörelsefrekvens. Vid en jämförelse mot tidigare forskning på rullskidor, var den vinkelräta kraften mot underlaget vid benfrånskjutet betydligt snabbare vid skidåkning på snö, även om den maximala kraften var likartad.

I *Studie III* utfördes saxningstekniken med en relativt smal vinkel mellan skidorna (”V”; 25-30°) och större delen av benfrånskjutskraften applicerades på framfotens insida. Av den totala framåtdrivande kraften genererades 77 % med benen och 23 % med överkroppen. Skidåkarna ökade rörelsefrekvensen från medel till maximal åkhastighet (från 1.20 till 1.60 åkcykler/sekund), medan åkcykellängden enbart ökades från medel till hög åkhastighet (från 2.0 till 2.3 m). Slutligen så är kraften genererad med benen en mycket viktig faktor vid både diagonalskidåkning och saxning, även om diagonalskidåkning kräver en snabbare kraftutveckling.

I *Studie IV och V* genomfördes tester med rullskidåkning på band där mekanisk verkningsgrad (d.v.s. energieffektivitet) och maximal syreupptagningsförmåga analyserades tillsammans med ett prestationstest som innefattade fyra lopp på en 1300 m simulerad sprintbana. Banan bestod av tre platta åkpartier med stakning (1°) åtskilda av två uppförsbackar (7°) med diagonalåkning. I *Studie IV* estimerades anaerob energiproduktion (s.k. syreskuld) vid åkning på sprintbanan. Sprintloppet genomfördes på 3:52 min:s där de aeroba och anaeroba bidragen till den totala energiproduktionen utgjorde 82 respektive 18 %. Det anaeroba bidraget resulterade i en ackumulerad syreskuld på 45 ml/kg kroppsvikt. Sprintprestationen var starkt relaterad till mekanisk verkningsgrad (53 %), åtföljd av syreupptagning (30 %) och syreskuld (15 %). Dessa resultat belyser starkt betydelsen av en hög energieffektivitet/åkekonomi för en hög prestationsförmåga inom sprintskidåkning.

I *Studie V* studerades farthållningsstrategier tillsammans med fysiologisk respons under fyra upprepade sprintlopp. Det första och sista loppet var snabbast (båda 3:48 min:s), relaterat till en större anaerob energiproduktion, där syreupptagningen var likartad under de fyra loppen. Den individuella variationen i sprintprestation var huvudsakligen (69 %) relaterad till olika grad av anaerob energiproduktion. En positiv farthållningsstrategi användes under samtliga sprintlopp och det individuellt snabbaste loppet genomfördes med en markant högre (5 %) utgångsfart över den första hälften av banan gentemot det långsammaste loppet. I tillägg reglerade skidåkarna arbetsintensiteten till olika banpartier, med en markant högre intensitet (~ 30 %) vid diagonalåkning uppför jämfört med de platta åkpartierna med stakning vilket resulterade i en mycket varierande anaerob energiproduktion. Sammanfattningsvis är en hög utgångsfart av stor betydelse vid sprintskidåkning. I tillägg är en hög arbetsintensitet i uppförsbackarna troligtvis än mer betydelsefullt vid skidprestation utomhus då en sådan strategi minskar den totala variationen i åkhastigheten och därmed även det totala luftmotståndet.

LIST OF PAPERS

This doctoral thesis is based on the following five studies, herein referred to by their Roman numerals:

Study I Andersson E., Supej M., Sandbakk Ø., Sperlich B., Stöggl T. & Holmberg H-C. 2010. Analysis of sprint cross-country skiing using a differential Global Navigation Satellite System. *Eur J Appl Physiol*, 110**,** 585-95.

Study II Andersson E., Pellegrini B., Sandbakk Ø., Stöggl T. & Holmberg H-C. 2014. The effects of skiing velocity on mechanical aspects of diagonal cross-country skiing. *Sports Biomech*, 13**,** 267-84.

Study III Andersson E., Stöggl T., Pellegrini P., Sandbakk Ø., Ettema G. & Holmberg H-C. 2014. Biomechanical analysis of the herringbone technique as employed by elite cross-country skiers. *Scand J Med Sci Sports*, 24**,** 542-52.

Study IV Andersson E., Björklund G., Holmberg H-C., Ørtenblad N. 2016. Energy system contributions and determinants of performance in sprint cross-country skiing. *Scand J Med Sci Sports.*

Study V Andersson E., Holmberg H-C., Ørtenblad N., Björklund G. 2016. Metabolic responses and pacing strategies during successive sprint skiing time trials. Submitted to *Med Sci Sports Exerc.*

ABBREVIATIONS

BW	Body weight
c.c.	Cross-country
CV	Coefficient of variation
d-GNSS	Differential Global Navigation Satellite System
DP	Double poling
DP_{kick}	Kick double poling
DP-V_{peak}	Peak velocity in DP during the 20-m acceleration test
G3-V_{max}	Maximal skiing velocity in gear 3
GPS	Global Positioning System
DS	Diagonal stride
e.g.,	Exempli gratia, for example
FIS	Fédération Internationale de Ski, International Ski Federation
G2-5	Gear 2-5 (the four main skating techniques)
GE	Gross efficiency
HB	Herringbone
i.e.,	Id est, that means, in other words
MAOD	Maximal accumulated oxygen deficit
O_2	Oxygen
RER	Respiratory exchange ratio
STT	Sprint time trial
V_{max}	Maximal skiing velocity
V_{peak}	Peak skiing velocity during an acceleration test
VO_2	Accumulated oxygen uptake
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
SD	Standard deviation

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1. INTRODUCTION

1.1. THE HISTORY OF CROSS-COUNTRY SKI RACING

The origin of cross-country (c.c.) skiing as a mode of transport dates back thousands of years to 2000 B.C. and introduced to reduce the energetic cost for daily activities such as travelling, hunting and fighting (Clifford, 1992). The historical overview by Formenti et al. (2005) describes how advances in c.c. skiing equipment have progressively decreased the energetic cost and increased the skiing velocity (Fig. 1), resulting in a velocity twice as high today as at a similar metabolic rate ~ 1500 years ago. The first known competition in c.c. skiing was held in Tromsø, Norway, in 1843 and the sport has been on the Olympic program since the first Winter Games (1924) in Chamonix (Clifford, 1992).

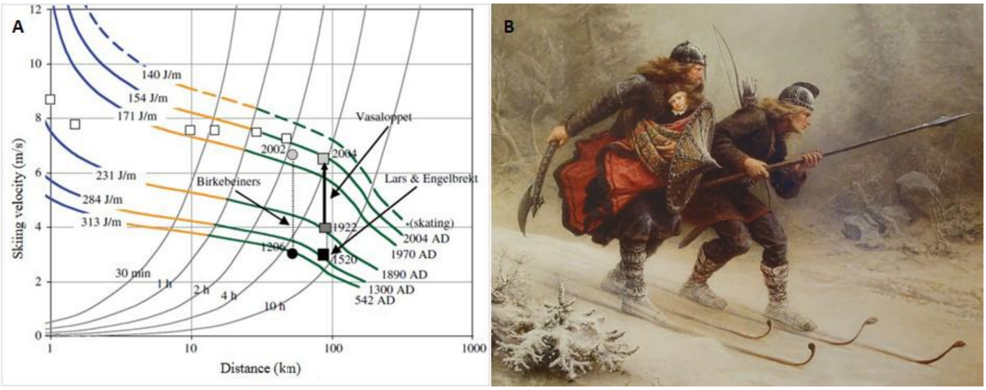

Figure 1. This figure is based on the previous work by Formenti et al. (2005). (A) The estimated relationships (three-colour curves) between skiing velocity and covered distance in relation to energetic cost (J/m) for different ski-equipment. This was obtained by using the available fraction of the maximal metabolic power (20.3 W/kg [~ 59 mL/kg/min]) used for different exercise durations (blue: 40 s to 10 min; light orange: 10 min to 1 h; green: 1 to 24 h, respectively). The squares represent current records in c.c. skiing, from sprint to long distance races. The black square represents the historical pursuit of Gustaf Vasa (1520 AD) and the circle represents the Birkebeiner skiers bringing the Norwegian prince child to safety. (B) The historical painting of the Birkebeiner skiers in 1206 AD.

During the late 1970s when machine-grooming became a regular way of preparing ski-tracks, the c.c. skating technique started to emerge and somewhat later during the 1980s the American skier Bill Koch transformed the sport by introducing the Marathon skating technique (i.e., skating with one ski in the classic track) (Fig. 2A). In the Winter Olympic Games in Sarajevo in 1984 the fastest skiers used skating over the flatter sections of the course, in combination with traditional classical skiing. Moreover, in the World Championships in Seefeld in 1985 all the medallists used the skating technique, with the best competitor using grip wax for classical skiing placed 24th (ISHA, 2016). To restrict the use of skating during competitions, it was banned over certain sections of a track. However, some athletes ignored this ban with dramatic consequences as described by the Swedish general of the International Ski Federation (FIS) Bengt Erik Bengtsson: *"At Lahti, Finland, in another World Cup race, skate-less zones were created. When an Italian racer skated through one, the Finnish coach grabbed him and threw him off the track"* (ISHA, 2016). Consequently, in May 1986, FIS divided c.c. skiing competitions into two different styles, the traditional classic and the new freestyle technique (i.e., skating). Since then skating (Fig. 2B) has been shown to be ~ 10% faster than classical skiing (Losnegard, 2013).

Figure 2. (A) The World Cup champion, Bill Koch, in 1982 employing the marathon skating technique. (B) The modern skating technique employed during a 50-km World Championship race in 2011.

1.2. THE SUB-TECHNIQUES EMPLOYED IN C.C. SKIING

C.c. skiing is a relatively complex endurance sport involving several different sub-techniques that are intermittently used during a race, according to the terrain and skiing velocity, in order to minimise energetic cost and improve finishing time (Bilodeau et al., 1992; Nilsson et al., 2004a). The skating style encompasses four different sub-techniques, or so-called gears (G2-5) (Nilsson et al., 2004a). The lower gears are used on uphill sections at slower velocities, while the higher gears are used on flatter and/or downhill sections at higher velocities (for a detailed description see Figure 7 in Chapter 3).

In the classical style there are also four different sub-techniques: double poling (DP), kick double poling (DP_{kick}), diagonal stride (DS) and herringbone (HB) (Fig. 3). The sub-technique that most closely resembles the basic locomotion patterns of walking and running is DS, where both arms and legs are involved in generating propulsion. Although not as frequently used as the other sub-techniques, HB is commonly required on steeper uphill terrain or when there is insufficient grip for DS. With HB the skis are angled outwards relative to the direction of skiing (as for skating) in order to attain adequate grip for propulsion. In DP propulsive forces are applied only through the poling action, making this technique well-suited for relatively flat terrain at high velocities, while the DP_{kick} is more effective on slight uphill gradients as a single leg kick is performed in connection to the poling action (Smith, 2003). The DP and DS sub-techniques are the two main classical sub-techniques used during training and racing.

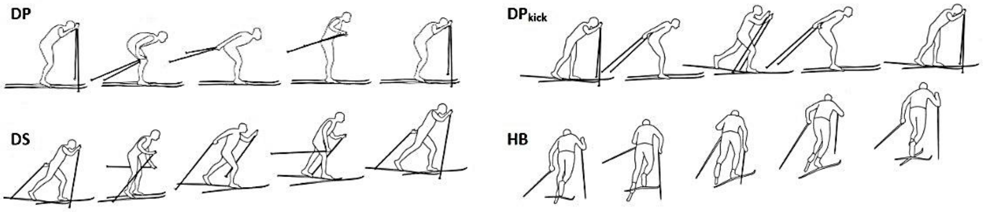

Figure 3. Schematisation of the different classical sub-techniques used in cross-country skiing. DP, double poling; DP_{kick}, kick double poling; DS, diagonal stride; HB, herringbone.

Skating is generally faster than classical skiing due to that the ski is always gliding with no need for grip wax, while with the classical technique the ski is briefly stationary for a period during the leg push-off. Moreover, the period during which legs generate force is considerably longer during skating (Bilodeau et al., 1992; Frederick, 1992; Smith, 2003).

1.3. NEW RACING FORMATS AND TECHNICAL DEVELOPMENTS

Since the mid-1900s c.c. skiing equipment has improved dramatically, from wooden to expensive high-tech skis made of composite and carbon-fibre materials. As early as 1992, Clifford described modern c.c. skiing as *"a world of high tech: lightweight composite skies, kewlar-wrapped poles, spandex tights, sophisticated boot/binding systems, neon colors, expensive fluorocarbon waxes"* and today this is even more true (Clifford, 1992). Furthermore, since the early 1990s competitions in c.c. skiing have changed rapidly with the introduction of several head-to-head competitions, including sprint, team sprint, skiathlon, and long-distance mass-start races. In fact, 10 of the 12 current Olympic c.c. ski races begin with a mass start (FIS, 2016). These rapid changes have altered the associated physiological, biomechanical and tactical demands on racing substantially. For instance, head-to-head competitions place greater demands on anaerobic capacity, explosive power and high maximal speed as the outcome of races is often decided in the final spurt (Rusko, 2003; Stöggl et al., 2006; 2007). Between the early 1990s and 2010, the average racing velocity during World Cup distance events has increased by ~ 5-8%, being ~ 20% faster in sprint than distance races (i.e., 10- or 15-km races for females and males, respectively) (Losnegard, 2013). These improvements most likely reflect advances in skiing equipment, changes in training regimes and newly-developed technical strategies, such as the "double-push" G3 skating (Stöggl et al., 2010; Stöggl et al., 2008), "running" DS (Stöggl et al., 2011) and "kangaroo" DP (Holmberg et al., 2005).

1.4. CURRENT DEMANDS AND TRAINING REGIMES

At present the most successful male distance c.c. skiers from Norway and Sweden demonstrate a maximal aerobic metabolic rate ($\dot{V}O_{2max}$) of ~ 80 to 90 mL/kg/min, although values tend to be lower for specialised sprint skiers due to a slightly larger muscle mass (Sandbakk & Holmberg, 2014). At the same time, upper-body strength, power and endurance have developed rapidly over the past two centuries (Losnegard & Hallén, 2014; Sandbakk & Holmberg, 2014; Stöggl et al., 2011) and to be successful today a c.c. skier must exhibit more extensive anaerobic and upper-body power, higher maximal speed and intelligent tactics in head-to-head races (Sandbakk & Holmberg, 2014). Maximal skiing velocity (V_{max}) over a short distance has been found to be highly related to sprint-skiing performance over a longer distance, which emphasises the need of strength and power in combination with technical ability (Sandbakk et al., 2011; Stöggl et al., 2007). In addition, more and more skiers have recently begun to use DP exclusively during the classical marathon races (40 to 90 km), without using grip wax. To meet these new demands, training has changed in a number of ways: 1) more specific training is carried out on roller-skis on race-specific terrain (i.e., roller-ski tracks); 2) more upper body strength and endurance training is completed; and 3) more systematic training is used to develop maximal skiing velocity (Sandbakk & Holmberg, 2014).

Altogether, these rapid developments in track preparation, equipment and training regimes have markedly enhanced racing performance. The associated demands require further scientific evaluation in order to provide both coaches and skiers with the basic "tools" necessary for the development of optimal training programs. The variations in environmental conditions, the topography of ski tracks, and the sub-techniques involved in c.c. skiing result in more complex demands than in most other endurance sports. Therefore, a combination of sophisticated measurements both in the field and in the laboratory are required to enhance the understanding of fundamental performance determinants in c.c. skiing.

1.5. AEROBIC ENERGY SUPPLY

Elite c.c. skiing is physiologically demanding, requiring a high $\dot{V}O_{2max}$, an ability to exercise for prolonged periods at a high fraction of $\dot{V}O_{2max}$ (i.e., well-developed endurance), considerable anaerobic capacity and power, as well as an effective movement economy that minimises the overall energy cost of skiing. Racing performance is closely related to the performance $\dot{V}O_2$ (i.e., the aerobic metabolic rate during a race), where the maximal limit is set by $\dot{V}O_{2max}$ (Joyner & Coyle, 2008). $\dot{V}O_{2max}$ is determined by a myriad of closely coordinated factors involved in the oxygen (O_2) transport chain (Wagner, 1996; 2000), including the capacity of the lungs to transfer O_2 from the air to blood, blood and erythrocyte volumes, the pumping capacity of the heart (i.e., cardiac output), the microcirculation that distributes blood to the muscles and O_2 extraction by the muscles (Wagner, 1991).

During exercise at sea level with a large engaged muscle mass, e.g., cycling, running or c.c. skiing, the predominant limitation of $\dot{V}O_{2max}$ has been proposed to be the maximal cardiac output (Bassett & Howley, 2000; Calbet et al., 2004). However, during c.c. skiing different sub-techniques are employed that differ in regard to propulsion and muscle recruitment. Consequently, $\dot{V}O_{2max}$ in each specific sub-technique may differ. For example, Holmberg et al. (2007) observed a 14% lower $\dot{V}O_{2max}$ during DP compared to DS.

Although $\dot{V}O_{2max}$ sets the upper limit for aerobic metabolic rate, the endurance of athletes can vary considerably (Joyner & Coyle, 2008). The aerobic capacity (i.e., endurance) of an athlete is reflected as the performance $\dot{V}O_2$ relative to $\dot{V}O_{2max}$, termed as the fractional utilisation of $\dot{V}O_{2max}$. A fractional utilisation of ~ 83% has been observed during 600-m simulated uphill (7°) sprint races on a treadmill with an average completion time of ~ 3 min (Losnegard et al., 2012a; McGawley & Holmberg, 2014) and a slightly higher value (88%) was reported for a 6-km simulated ski-race with an average duration of ~ 23 min (Welde et al., 2003). During distance races (15 to 50 km for males) the fractional utilisation decreases with increasing distance, being ~ 10% lower for the longest compared to the shortest distance (Rusko, 2003).

1.6. ECONOMY OF MOVEMENT AND GROSS EFFICIENCY

Gross efficiency (GE) is a highly important determinant of sports performance and describes the degree to which metabolic rate is transferred to external power or velocity (Coyle, 1999; Gaesser & Brooks, 1975; Joyner & Coyle, 2008). Previous findings indicate that when power output can be determined, GE provides a better measure of whole-body efficiency in endurance sports than delta and/or net efficiency (Ettema & Lorås, 2009; Sandbakk et al., 2010). An alternative concept is movement economy or O_2 cost, usually expressed in terms of the $\dot{V}O_2$ at a given velocity or VO_2 per distance covered (di Prampero et al., 1986; Saunders et al., 2004). In the context of treadmill roller skiing, one direct advantage of using GE instead of an expression of economy is that results can be more easily compared between different studies, as the computation accounts for differences in rolling resistance and work against gravity.

In both distance running and c.c. skiing the $\dot{V}O_2$ at a given velocity varies considerably (up to ~ 35%) between individuals (Conley & Krahenbuhl, 1980; Daniels, 1985; Farrell et al., 1979; Hoffman et al., 1990; Sjödin & Svedenhag, 1985), which is also the case for GE or economy in a less complicated movement such as cycling (~ 25% variation) (Coyle et al., 1992; Lucia et al., 2002). Additionally, Sandbakk et al. (2010) observed a significantly higher GE for international- than national-level c.c. skiers.

During cycling the percentage of slow-twitch muscle fibres have been shown to be positively related to GE (Coyle et al., 1992) and when running, leg mass is positively related to energy cost (Larsen, 2003). However, the factors that influence economy or GE with the various sub-techniques of c.c. skiing remain to be examined. In endurance athletes, GE and/or economy may be improved by several years of training (Ainegren et al., 2013b; Coyle, 2005; Jones, 2006), probably due to technical and/or physiological adaptations that minimise energy expenditure (Almåsbakk et al., 2001; Coyle et al., 1992). In addition, inverse relationships between $\dot{V}O_{2max}$ and GE and/or economy have been documented in world-class cyclists and elite runners of a similar performance (Lucia et al., 2002; Morgan & Daniels, 1994).

In the case of c.c. skiing, evaluating the impact of GE on race performance is rather complicated due to the different sub-techniques that are employed at various gradients and velocities. In such an assessment, GE in the associated skiing sub-techniques have to be analysed over several different submaximal velocities and/or inclines. For example, Ainegren et al. (2013b) showed that an elevated slope gradient may increase the GE of skiing with the DS or G3 sub-techniques. In addition, during fast DP skiing, high muscle contraction velocities may reduce the mechanical efficiency of the muscles involved (Hill, 1922), thereby lowering GE similarly as observed for cycling at high cadences (Chavarren & Calbet, 1999; Ettema & Lorås, 2009).

1.7. ANAEROBIC ENERGY SUPPLY

Performance in endurance sports is closely associated with the rate of aerobic energy supply (Joyner & Coyle, 2008), while the overall significance of anaerobic energy supply is considered to be lower. During distance ski races the level of blood lactate, which is used as a surrogate marker of anaerobic energy production, rises rapidly to 5-10 mmol/l during the first 10 min and increases more slowly thereafter up to 7-19 mmol/l immediately following a 15-km race (Mygind et al., 1994; Rusko, 2003). Although the overall contribution of anaerobic energy during distance c.c. ski races is low relative to the aerobic contribution, the work intensities of ~ 110-130% of $\dot{V}O_{2max}$ observed over short uphill sections indicate a considerable generation of anaerobic energy (Norman et al., 1989; Rusko, 2003). These anaerobic bursts are made possible by anaerobic recovery on downhill stretches (with regeneration of phosphocreatine stores and clearance of blood lactate via subsequent oxidation) (Rusko, 2003; Sahlin et al., 1979). Accordingly, the varying work intensities involved in c.c. skiing are likely to enhance the importance of anaerobic energy production. Indeed, Björklund et al. (2011) demonstrated superior blood lactate recovery in elite compared to moderately-trained skiers roller skiing at variable intensity.

In contrast to aerobic energy, the supply of anaerobic energy is limited by the availability of substrates and accumulation of their metabolic by-products, which means that the relative anaerobic energy contribution declines with longer exercise duration (Gastin, 2001). In running, for example, anaerobic metabolism accounts for ~ 40% and ~ 23% during 800-m and 1500-m events, respectively (Duffield et al., 2005a; 2005b). The contribution from aerobic energy pathways during exercise can easily be quantified on the basis of $\dot{V}O_2$, while the assessment of anaerobic energy is more complicated. The most frequently used approaches for estimating maximal anaerobic energy production during supramaximal whole-body exercise are the maximal accumulated O_2 deficit (MAOD) and GE methods (Medbø et al., 1988; Serresse et al., 1988).

Anaerobic energy contributions during simulated uphill sprint c.c. skiing time trials (600 m, 7°), lasting ~ 3 min, have been shown to be ~ 22% and ~ 26% with G2 and DS, respectively (Losnegard et al., 2012a; McGawley & Holmberg, 2014). In addition, anaerobic capacity has been identified as the key predictor of sprint-skiing performance (Losnegard et al., 2012a). However, the overall importance and distribution of anaerobic energy production during sprint c.c. skiing with different sub-techniques on varying terrain requires further investigation.

1.8. PACING STRATEGIES

In connection with maximal performances over durations similar to sprint skiing (i.e., ~ 2-4 min), a fast start with subsequently declining velocity (i.e., positive pacing) is beneficial for performance (Abbiss & Laursen, 2008; Bishop et al., 2002; de Koning et al., 1999; Tucker & Noakes, 2009). An analysis of the men's 800-m world records revealed that 26 out of 28 records involved positive pacing with a substantial slowing down during the final 400 m (Tucker et al., 2006). In addition, as the event duration approaches 4 min the pacing strategy becomes more even (Abbiss & Laursen, 2008; Tucker & Noakes, 2009).

For endurance performance over an undulating course and/or with varying wind resistance, a variable pacing strategy is usually employed (Abbiss & Laursen, 2008). The undulating terrain and various sub-techniques employed during sprint races in c.c. skiing make pacing even more complex than in other endurance sports. No intermediate times are currently provided during sprint events, which limits the possibility for detailed analyses of skiers' technical and tactical strategies. One possibility for providing more detailed performance analyses of pacing in the field is the differential global navigation satellite system (d-GNSS), which has a superior measurement accuracy compared to conventional global positioning system (GPS) devices (Terrier et al., 2000; Terrier & Schutz, 2003; Terrier et al., 2005; Takac et al., 2005). Such measurements, in combination with laboratory assessments of metabolic responses associated with self-selected pacing during sprint skiing on a simulated treadmill course with a varied topography, would provide novel insights into the distribution of energetic resources and its relationship to performance.

1.9. THE BASIC MECHANICAL PRINCIPLES OF C.C. SKIING

When a skier applies forces to the ground, the reaction force generated in the direction of movement (i.e., propulsive forces) is largely determining the velocity (Smith, 2003). A number of mechanical factors exert direct and indirect effects on the resulting performance (Frederick, 1992). Gravity is normally the major constraint on performance, propelling the skier downhill and resisting the skier during the uphill. The second most significant factor is the snow friction that limits ski glide. The component of snow friction is the sum of dry friction, wet friction together with impact and compression resistance when the ski compresses the snow surface. The influence of each respective factor varies with snow type, temperature and humidity, making ski selection and waxing crucial to racing performance (Buhl et al., 2001; Smith, 2003). The third factor restricting performance is aerodynamic drag, which at high downhill skiing velocities becomes more important than snow friction. Aerodynamic drag can be minimised by using a tucked position when gliding downhill, using an aerodynamic racing suit and/or by following closely behind another skier (Bilodeau et al., 1994; Frederick, 1992). In addition, pacing strategies designed to minimise overall variation in racing velocity may improve c.c. skiing performance by lowering aerodynamic drag as previously has been observed when modelling cycling performance (Atkinson et al., 2007a; Atkinson et al., 2007b; Boswell, 2012; Swain, 1997) and c.c. skiing performance (Sundström et al., 2013).

1.10. SELECTION OF SUB-TECHNIQUES IN C.C. SKIING

In c.c. skiing a specific sub-technique is mechanically and energetically beneficial for specific types of terrain and/or velocities (Smith, 2003). The skier's velocity over a race course is determined by a combination of resistive forces together with the metabolic power and GE (Frederick, 1992; Sundström et al., 2013). With any given sub-technique the ability to apply forces is largely dependent on the skiing velocity, since the time of force generation and magnitude of force is related to the force-velocity or power-velocity relationships of muscles (Hill, 1922; Østerås et al., 2002).

When c.c. skiing uphill, pole forces are applied more effectively with DS than DP. With DP a greater amount of the total work is generated by the upper body and forces may exceed the physiological optimum (Pellegrini et al., 2013). Another negative aspect of DP during uphill skiing is that the phase of deceleration during each movement cycle is higher due to the shorter relative phase of propulsion than for DS, which also involves propulsion generated by the legs (Hoffman et al., 1994; Millet et al., 1998b). These factors probably exert a direct influence on the energetic cost of the classical DP sub-technique, making it less economical than DS on inclines steeper than 3° (Pellegrini et al., 2013).

Although selection of and transitions between sub-techniques are a unique characteristic of c.c. skiing, the influence of skiing velocity, incline and energetic cost in relation to transitions during exhaustive sprint-skiing time trials have, to our knowledge, not yet been evaluated in the field and/or the laboratory. Minimisation of energetic cost has been proposed to be the main factor determining transitions between walking and running (Bramble & Lieberman, 2004; Margaria, 1976). However, the comfort of locomotion is likely to be more dominant than energetic cost in determining such transitions (Minetti et al., 1994). Moreover, in the context of classical c.c. skiing, Pellegrini et al. (2013) recently showed that biomechanical constraints for pole and leg force application were more related to the selection of sub-techniques. Altogether, the choice of sub-technique used during c.c. skiing is based on complex interactions between skiing velocity, slope gradient and the physiological as well as biomechanical ability to generate forces (Cignetti et al., 2009; Kvamme et al., 2005; Pellegrini et al., 2013). Hence, an additional challenge for the c.c. skier is not only to decide when to change sub-technique, but also to manage the biomechanical and physiological changes for the muscles involved (Björklund et al., 2015; Björklund et al., 2010; van Hall et al., 2003).

1.11. KINETIC ASPECTS OF C.C. SKIING

The classical sub-techniques with the greatest reliance on the upper-body for generating propulsion are DP and DP_{kick}. In DP all propulsion is generated axially through the poles over ~ 0.47 s at 15 km/h (Lindinger et al., 2009b; Millet et al., 1998b; Nilsson et al., 2004a) to 0.25 s at 29 km/h (Lindinger et al., 2009b). The generated peak pole forces are ~ 25-50% of an individual's body weight (BW) (Holmberg et al., 2005; Millet et al., 1998b; Stöggl & Holmberg, 2016), with a propulsive component of ~ 55% of the mean axial resultant force (Stöggl & Holmberg, 2016). With DP_{kick} employed at a moderate uphill (3°), the peak pole force ranges between 22-28% of

BW and is increasing with elevated velocities (from 13 to 19 km/h) (Göpfert et al., 2013).

The vertical peak leg-thrust forces generated during DS are 200-300% of BW, while the propulsive peak force is only 10-25% of BW (Smith, 2003; Pierce et al., 1987). In order to generate this propulsive force, the ski must be stationary for a brief period (~ 0.10-0.25 s) (Komi, 1987; Komi & Norman, 1987; Nilsson et al., 2004a; Vähäsöyrinki et al., 2008) and the grip-waxed midsection of the ski has to attach to the snow momentarily. This vertical force component is important for creating sufficient static friction to avoid slipping, which differs from roller skiing with ratcheted wheels (Ainegren et al., 2013a). The pole forces associated with DS on snow are 13-17% of BW with a propulsive component of ~ 65% (Pierce et al., 1987). Therefore, leg thrust forces are considerably greater than pole forces, a larger proportion of the axial poling force is propulsive.

The HB technique is required on steeper uphill terrain and/or when the grip is insufficient to allow DS. In such cases, the skis are angled outwards in relation to the direction of skiing in order to achieve sufficient static friction to allow propulsion and, in contrast to the lateral push-off when skating, the skis are not allowed to glide (FIS, 2016). To date, the biomechanical aspects of the HB sub-technique have not been examined in detail.

During G2 skating uphill, leg-thrust forces are applied over an ~ 70% longer time than during DS and pole forces are ~ 2-4 times greater, contributing to ~ 60% of the total propulsion (Smith, 1992). However, Stöggl & Holmberg (2015) recently reported that pole forces contribute to 44% of the total propulsion in G2. The force effectiveness (i.e., the ratio between propulsive and resultant forces) was noticeably higher for the pole than leg forces (~ 59% versus 11%), with resultant peak-pole and leg-thrust forces of ~ 34% and ~ 140% of BW, respectively. Moreover, the contribution of the upper body to total propulsion may be even greater for uphill skiing with G3, emphasising the importance of well-developed upper-body strength and endurance (Smith, 2003).

1.12. KINEMATIC ASPECTS OF C.C. SKIING

Speed (m/s) of c.c. skiing is equal to cycle length (m) multiplied by cycle rate (cycles/s [Hz]) (Bilodeau et al., 1996). Several studies (Bilodeau et al., 1996; Lindinger et al., 2009a; Norman et al., 1989; Sandbakk et al., 2010; Smith, 1992) evaluating the skating and/or classical styles of c.c. skiing have revealed that faster skiers generate longer cycle lengths with more powerful leg and/or pole thrusts, while the cycle rate for skiers of different levels is relatively similar. With all sub-techniques skiers may regulate velocity primarily by adjusting the cycle rate (Hoffman et al., 1995; Millet et al., 1998b; Nilsson et al., 2004a). However, recent studies (Lindinger & Holmberg, 2011; Lindinger et al., 2009b; Vähäsöyrinki et al., 2008) have shown that elite skiers regulate the velocity by adjustments of both cycle rate and cycle length up to high velocities, while the increase from high up to maximal velocities mainly relies on an elevated cycle rate (Lindinger et al., 2009b; Vähäsöyrinki et al., 2008).

In an analysis of a World Cup sprint competition, Zory et al. (2005) found a positive correlation between cycle rate and DS velocity, where cycle rate was also related to overall performance, but there was no evident relationship between cycle length and performance. Thus, the fastest skiers generated sufficient force to conserve cycle length at a higher cycle rate, despite the shorter time for generating propulsive forces. In addition, in order to maintain the duration and momentum of the leg thrust while increasing the velocity of uphill (7°) DS roller skiing from high to maximal, skiers adopt a high-frequency running DS technique without gliding, i.e., utilising a substantially higher cycle rate and shorter cycle length (Stöggl et al., 2011).

Although a long cycle length is important for DS skiing performance (Lindinger et al., 2009a), an increased cycle rate is probably more important for generating high maximal velocities (Stöggl et al., 2011). This may be even more essential in the case of steep uphill skiing, since a high cycle rate minimises the absolute duration of the non-propulsive deceleration phase (Zory et al., 2005) and large oscillations in kinetic energy are costly from a metabolic standpoint (Frederick, 1992). The HB sub-technique, which is usually employed on the steepest uphill sections, lacks a gliding phase; this limits the possibility of increasing cycle length, so that adaptation of cycle rate may be more important in regulating velocity.

A fundamental question in connection with all skiing techniques is how velocity is regulated. Nevertheless, only Vähäsöyrinki et al. (2008) have examined the effects of different velocities on both the kinematics and kinetics of DS on snow. However, that study was performed on an incline of 2.5°, where elite skiers would normally use the DP_{kick} or DP sub-techniques (Göpfert et al., 2013; Smith, 2003). Therefore, a similar biomechanical investigation at a gradient on which DS is normally performed would be informative.

1.13. THE COMPLEXITY OF C.C. SKIING PERFORMANCE

A schematic illustration of the various key factors that influence performance in c.c. skiing is illustrated in Figure 4. Skiing velocity is directly related to power output and mechanical constraints (Frederick, 1992). The power output is set by the total metabolic rate multiplied by the GE, which are each further related to several physiological and biomechanical factors. The regulation of velocity (i.e., pacing) and hence the metabolic rate is set by a feedback control system between the central nervous system and the skeletal muscles in order to optimise performance in relation to the duration and physiological resources, as well as to avoid critical metabolic disturbances that may lead to a deterioration in performance (Noakes et al., 2005; St Clair Gibson et al., 2006; Tucker & Noakes, 2009; Ulmer, 1996). Although performance in all endurance sports is set by a complex integration of governing, mechanical, biomechanical and physiological factors, performance in c.c. skiing is even more complex due to the different sub-techniques involved, the variety of course distances and terrain, the varying external conditions and the importance of proper selection and preparation of skis.

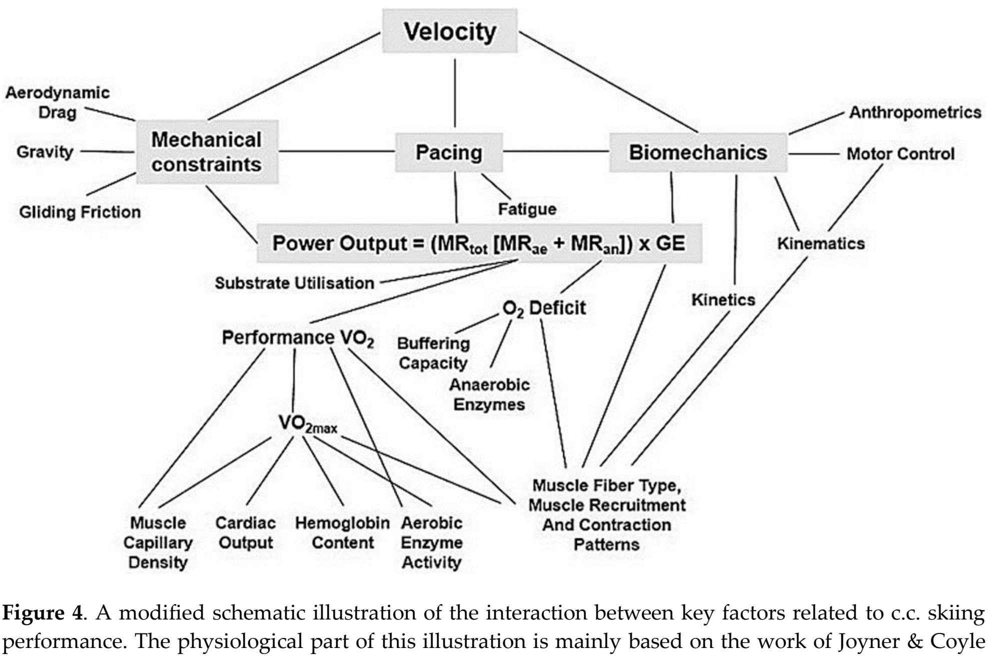

Figure 4. A modified schematic illustration of the interaction between key factors related to c.c. skiing performance. The physiological part of this illustration is mainly based on the work of Joyner & Coyle (2008). Abbreviations: MR_{tot}, total metabolic rate; MR_{ae}, aerobic metabolic rate; MR_{an}, anaerobic metabolic rate; GE, gross efficiency.

1.14. DIFFERENCES BETWEEN C.C. SKIING ON SNOW AND ROLLER SKIING

Skiers use roller skiing for training and testing due to the close similarities to c.c. skiing on snow (Mahood et al., 2001; Millet et al., 2002). However, one major difference between the two skiing modes involves the components of friction (Dillman & Dufek, 1983). Roller skiing encompasses work against rolling resistance, while skiing on snow involves gliding resistance, which is more complex and relatively difficult to quantify. The coefficient of rolling resistance of a pre-warmed roller ski is influenced slightly by the normal force (i.e., the weight of the skier), decreasing linearly with greater loading (Ainegren et al., 2008). By contrast, the coefficient of snow friction is lower for heavier skiers than that for lighter skiers only at temperatures below -6°C, with no clear dependency of loading on the gliding properties at warmer temperatures (Buhl et al., 2001). In addition, the resistance for gliding on snow is lowest at a surface temperature of ~ -3° C.

To avoid compromising internal validity due to changing weather conditions, many recent investigations on c.c. skiing have been performed indoors using roller skis on large treadmills (Ainegren et al., 2013b; Björklund et al., 2010; Holmberg et al., 2005; Lindinger et al., 2009b; Sandbakk et al., 2010; Stöggl et al., 2011; McGawley & Holmberg, 2014; Mourot et al., 2015). Although tests in such a controlled environment exhibit high internal validity, the external validity may be questionable, since roller skiing does not exactly replicate skiing on snow (Ainegren et al., 2013a). Therefore, field measurements are highly important for developing our knowledge of the physiological and biomechanical responses to c.c. skiing on snow.

2. AIMS

The overall aim of the present thesis was to further our current understanding of the biomechanical and physiological factors that influence c.c. sprint-skiing performance in the field and in the laboratory.

The general aims of the studies were as follows:

1. (a) To describe skiing velocities and choice of sub-techniques during a simulated skating sprint time trial (STT) on snow; (b) To describe the relationships of these factors, as well as $\dot{V}O_{2max}$ and speed capacity to performance (*Study I*).

2. To evaluate the biomechanics of velocity adaptation during DS and HB on snow, as well as to characterise the biomechanics of HB in greater detail (*Studies II* and *III*).

3. To assess the contributions of aerobic and anaerobic energy during a classical 1,300-m STT on a simulated undulating treadmill course and to determine the O_2 deficit using a novel GE approach (*Studies IV* and *V*).

4. To evaluate the relative impact of $\dot{V}O_2$, O_2 deficit and GE on STT performance (*Study IV*) and to describe the metabolic response associated with self-selected pacing strategies during four successive 1,300-m STTs (*Study V*).

The aims and hypotheses are described in greater detail in the individual articles.

3. METHODS

3.1. PARTICIPANTS

In the present thesis a total of 33 male c.c. skiers competing in sprint and distance races at a national or international level volunteered to participate (some were involved in more than one study) and their characteristics are documented in Table 1. *Study I* included four members of the Swedish National Team, *Studies II* and *III* included elite Norwegian c.c. skiers and *Studies IV* and *V* included well-trained Swedish skiers. All studies were conducted in accordance with the Declaration of Helsinki and were pre-approved by the Regional Ethical Review Board of Umeå University, Umeå, Sweden.

Table 1. Characteristics of the male participants included in *Studies I-V, mean ± SD*.

	N	Age (yr)	Body mass (kg)	Body height (m)	$\dot{V}O_{2max}$* (mL/kg/min)
Study I	9	25.9 ± 3.5	74.5 ± 6.2	1.81 ± 0.05	73.4 ± 5.8
Study II	11	23.5 ± 4.8	77.4 ± 6.9	1.81 ± 0.06	72.1 ± 4.6
Study III	11	23.2 ± 4.4	78.2 ± 7.5	1.82 ± 0.05	73.5 ± 5.2
Study IV	11	24.3 ± 3.6	78.7 ± 5.9	1.82 ± 0.05	64.9 ± 4.0
Study V	10	24.6 ± 3.5	80.1 ± 5.8	1.83 ± 0.05	64.9 ± 6.3

* determined with diagonal stride roller skiing on a treadmill

3.2. STUDY OVERVIEW

3.2.1. In the field

Study I involved two days of testing with a $\dot{V}O_{2max}$ test and three performance tests on snow, including maximal speed tests over 20 m in G3 and DP, respectively, followed by a 1,425-m skating STT. A d-GNSS that was synchronised with video recordings was used to evaluate skiing velocity and gear selection.

Study II involved biomechanical measurements during c.c. skiing on snow using DS on a 50-m uphill slope (7.5°), with data analysed from the final 20 m. Each skier performed the test at maximal (100%), high (80% of maximal) and moderate (65% of maximal) velocities.

Study III involved skiing up a slope on snow, employing DS for 40 m at an incline of ~ 7.5° followed by 10 m of skiing with HB at an incline of ~ 15°. The skiing over the last 8 m of this slope was analysed. All skiers performed three separate trials at similar relative intensities as those used in *Study II*. Kinematics and kinetics of uphill c.c. skiing at the three different relative velocities were analysed through measurements of pole and plantar forces that were time synchronised with video recordings (*Studies II* and *III*).

3.2.2. In the laboratory

Studies IV and *V* included a series of laboratory tests where skiers were tested on a treadmill, employing roller skiing during five separate test days over three weeks. The first four test days served as pre-tests for the main sprint performance test, which involved four self-paced 1,300-m STTs using the DP and DS sub-techniques on a simulated course consisting of 70% flat (1°) and 30% uphill (7°) terrain. Treadmill velocity and $\dot{V}O_2$ were measured during the STTs. Pre-tests were used to assess the technique-specific $\dot{V}O_{2max}$, GE and V_{max}, as well as to familiarise the skiers with the course. In addition, the effects of velocity and incline on GE in the two different sub-techniques were assessed for the purpose of the anaerobic energy calculations in the STT. The aerobic and anaerobic energy contributions and determinants of performance were evaluated (*Study IV*), together with the metabolic responses in relation to pacing strategies and performance (*Study V*).

3.3. EQUIPMENT

3.3.1. In the field

Ski track and skiing equipment. In *Study I* a simulated sprint c.c. skiing competition using the skating technique was performed on snow for two laps on an undulating 712.5-m course consisting of approximately equal amounts of flat, uphill and downhill terrain. The maximal height difference between the lowest and highest points was 17 m with a total climb of 26 m per lap. On the basis of terrain properties, each lap was divided into 10 different sections (S1-S10) marked with reference poles.

In *Studies I-III* skiers used their own racing poles and skis with standardised and appropriate glide and grip wax applied by a professional ski technician. All testing was performed on single days under stable weather conditions and tracks were machine-groomed on the evenings prior to testing.

Time measurements. In *Study I* a d-GNSS was used to analyse skiing velocity and position on the course. The d-GNSS system was time synchronised with continuous video recording (Panasonic NV-GS 280, Osaka, Japan) from a snow-mobile. The d-

GNSS system (Leica Geosystems AG, Heerbrugg, Switzerland) uses signals from both the United States and Russian global navigation systems (GPS and GLONASS) with a high measurement accuracy (Takac et al., 2005). The skiers wore the rover of the d-GNSS system in a specially-designed small backpack (total weight ~ 1.64 kg).

In *Studies II* and *III* two pairs of photocells (IVAR, LL Sport, Mora, Sweden) provided section times and average velocities. In addition, the trials were filmed continuously using a panning camera (Panasonic NV-GS 280, Osaka, Japan). *In Study III* two cameras (Sony Handycam HDR-HC1E PAL, Tokyo, Japan) were fixed perpendicularly to one another to allow a three-dimensional video reconstruction.

Kinematics and kinetics. In *Studies II* and *III* kinematic values were obtained from the pole and plantar force measurements providing cycle times and phase durations for the poling, gliding and kick phases (for further details, see section 3.5). In addition, pole angles and the angles between body segments were analysed in *Study III* by a three dimensional video reconstruction (SIMI Reality Motion System GmbH, Unterschleissheim, Germany).

In *Studies II* and *III*, custom-designed poles with a strain-gauge load cell (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) mounted directly below the grip monitored ground reaction forces at a rate of 1500 Hz. The plantar pressure of each leg was recorded at 100 Hz using the Pedar Mobile System (Novel GmbH, Munich, Germany) and then converted to plantar force in the normal direction to the surface of the insole by multiplying pressure by area. In the current thesis plantar force is referred to as leg force. The area of the foot was divided into forefoot and rear-foot halves and inside- and outside-foot areas. The pole and plantar measuring systems were validated according to Holmberg et al. (2005). Plantar insoles were calibrated using a Pedar device with homogenous air pressure using a computer-aided procedure. The kinetic and kinematic parameters were analysed during the same skiing cycles. All data were processed using the IKE-Master Software (IKE-Software Solutions, Salzburg, Austria) and Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA).

3.3.2. In the laboratory

Treadmill and skiing equipment. All of the laboratory tests in *Studies I* and *III-V* were performed on a motor-driven treadmill designed specifically for roller skiing

(Rodby Innovation AB, Vänge, Sweden). Pro-Ski C2 roller-skis (Sterners, Dala-Järna, Sweden) equipped with either NNN (Rottefella, Klockarstua, Norway) or SNS (Salomon, Annecy, France) binding systems were used. The rolling resistance for the two sets of roller skis was similar and determined as described previously by Ainegren et al. (2008). Before testing, the roller skis were pre-warmed for at least 60 min in a heating box to avoid subsequent changes in resistance of the wheels and bearings due to a warm-up effect. The skiers used their own poles (equipped with special carbide tips) during all the roller-skiing tests. In *Studies IV* and *V*, self-pacing was possible with lasers that automatically increased (0.68 km/h/s) or decreased (0.40 km/h/s) the velocity when the athlete moved to the front or rear of the treadmill belt, respectively, maintaining a constant velocity otherwise.

Physiological measurements. In *Studies I* and *III-V*, all respiratory variables were measured using an AMIS 2001 model C (Innovision A/S, Odense, Denmark) ergospirometry system, which was calibrated before each test according to the specifications of the manufacturer. Ambient conditions were monitored with an external apparatus (Vaisala PTU 200, Vaisala Oy, Helsinki, Finland). Fingertip blood samples (20 µl) were used for the determination of blood lactate concentration using a Biosen 5140 analyser (EKF diagnostic GmbH, Magdeburg, Germany). Heart rate was measured with heart-rate monitors (model S610 or S810, Polar Electro Oy, Kempele, Finland).

3.4. MEASUREMENTS AND PROTOCOLS

3.4.1. In the field

Study I involved three different tests: 1) a maximal velocity test using the skating G3 sub-technique (G3-V_{max}) on flat terrain, where the skier was instructed to accelerate over a 100-m section and to reach maximal velocity when entering the 20-m measurement zone; 2) a 20-m acceleration test with a standing start on flat terrain with the DP sub-technique (DP-V_{peak}), with the skier being instructed to accelerate maximally over this section; and 3) a single STT employing the skating style. The d-GNSS equipment provided maximal, peak and average velocities during all testing. Both the G3-V_{max} and DP-V_{peak} tests were carried out twice, each separated by four minutes of light activity. During the STT, heart rate was monitored continuously and blood lactate concentration was determined 1, 3 and 5 min after the finish.

In *Studies II* and *III* the skier performed skiing over a short (50-m) uphill slope at three relative velocities (65%, 80% and 100% of maximal) using either DS or DS together with HB. Trials were repeated if the skier deviated extensively from the predetermined velocity (by 10% for DS and 5% for HB). The relative velocities were similar to those normally used in distance races (65-80% of maximal) or sprint races (80-100% of maximal). Prior to testing, each skier performed a 15-min warm-up at 60-75% of maximal heart rate and each trial was separated by 6 min of light active recovery (~ 50% of maximal heart rate).

3.4.2. In the laboratory

In *Studies I-III*, $\dot{V}O_{2max}$ during DS roller skiing was determined at a fixed velocity of 11 km/h and an initial treadmill incline of 4°, which was raised by 1°/min. In *Studies IV* and *V* the tests of $\dot{V}O_{2max}$ with DP or DS started at velocities of 21 or 9 km/h and at fixed inclines of 1° or 7°, respectively, with subsequent increases of 1 km/h every 60 s with DP or 0.5 km/h every 45 s for DS until exhaustion. The average of the three highest consecutive 10-s $\dot{V}O_2$ values was defined as $\dot{V}O_{2max}$ (*Studies I-V*).

In *Studies IV* and *V*, five different tests were performed on separate days, with the first four serving as pre-tests for the final STT performance test. Submaximal $\dot{V}O_2$ and $\dot{V}O_{2max}$ in DP and DS were determined. All of the DP and DS roller-skiing tests were performed on fixed gradients of 1° and 7°, respectively. Gas exchange (i.e., $\dot{V}O_2$ and $\dot{V}CO_2$) was analysed during the last minute of each submaximal stage. For DP, a 5-min warm-up at 17 km/h was followed by the submaximal test that began at 19 km/h, with an increase by 1 km/h every 4-min up to a velocity of 22 km/h and thereafter by 0.5 km/h every 4 min until the highest steady-state velocity or highest pre-programmed skiing velocity of 26.5 km/h was reached. For DS, submaximal $\dot{V}O_2$ was determined during five continuous 4-min workloads, or up to a respiratory exchange ratio (RER) ≤ 1.00 (McArdle et al., 2010). Following a 5-min warm-up at 7.0 km/h, the test started at 7.5 km/h, with subsequent workload increases of 0.5 km/h. The submaximal tests were used to determine the relationship, based on the seven last stages in DP and five stages in DS, between velocity and GE for assessing anaerobic energy production during the STT performance tests on test day 5 (for further details see section 3.5).

To evaluate the impact of incline on GE and energetic cost, submaximal $\dot{V}O_2$ was measured during DP or DS skiing for an initial 10-min workload at 16.0 or 9.5 km/h and 1.4° or 3.5°, respectively, with subsequent increases by 0.4° or 0.7° every 5 min. This test was continued for six workloads or up to the highest steady-state intensity with a RER ≤ 1.00. The relationships between gradient, GE and energetic cost were assessed by regression and utilised for calculations concerning the technique transitions, when the gradient was changing, during the STT performance test.

Tests of V_{max} were performed using DP (1°) and DS (7°). After a self-paced warm-up (~ 18 min) followed by a 2-min passive recovery, the test with DP or DS began with 20 s at 22.5 km/h or 14 s at 12.0 km/h, with subsequent increases of 1.5 km/h every 10 s or 1.0 km/h every 7 s, respectively, until exhaustion. Following this testing, each participant became familiarised with the STT test, by performing two maximal 1,300-m STTs (as described below), using the same warm-up and cool-down procedures as on test day 5. The order of sub-technique was randomised and similar during all the four pre-tests.

The four STT performance tests were completed over a simulated 1,300-m sprint course (Fig. 5) that consisted of five different sections (S1–S5) involving the DP and DS sub-techniques intermittently, thereby requiring four transitions (T1-T4) and a start-up phase (S). The skiers were only allowed to use the DP and DS sub-techniques, i.e., DP_{kick} was not allowed to use during the transitions. The participants were instructed to use DP on S1, S3 and S5 and DS on S2 and S4. Before the first STT, a 15-20-min warm-up over 3900 m (three times the course) was conducted at a self-selected velocity, with the warm-ups prior to the subsequent next three STTs consisting of one self-paced STT "lap" (1,300 m). The total time for cool-down (one self-paced "lap"), passive recovery and warm-up between trials was 45 min. Each participant could follow his velocity and position on the course on a large computer screen in front of the treadmill. $\dot{V}O_2$ was measured continuously during the STT and the time elapsed and distance travelled was recorded by a computer at 2.5 Hz.

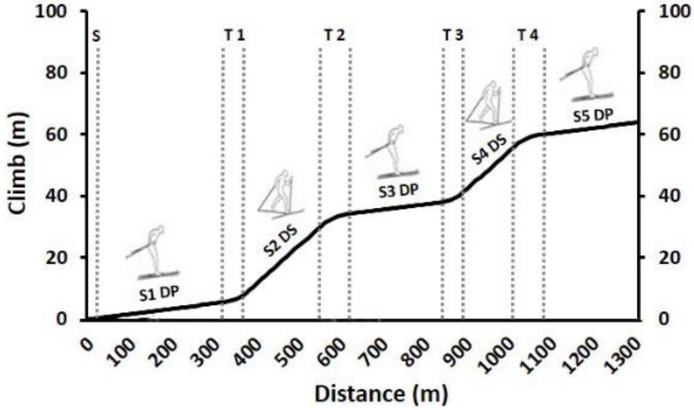

Figure 5. The sprint time trial (STT) course profile. The vertical lines indicate the start-up of the treadmill (s) and the four transitions (T1-T4) between the three sections (S1, S3 and S5, 1° incline) of double poling (DP) and the two sections (S2 and S4, 7° incline) of diagonal stride (DS).

3.5. CALCULATIONS (FOR DETAILS, SEE *STUDIES II-V*)

In *Studies II* and *III* absolute cycle time (CT), poling/leg thrust, gliding (only during DS in *Study II*) and recovery times, cycle rate (the reciprocal of CT) and cycle length (the product of CT and skiing velocity) were determined. Relative time phases (% of CT) for poling, arm swing, gliding (only during DS), pre-loading (only during DS in *Study II*), kick and leg swing were calculated by dividing the durations for the separate phases by the CT (see Fig. 6). The average right and left pole and leg forces for each subject over five cycles (in *Study II*) or four cycles (in *Study III*) of skiing were combined. Pole and leg force impulses during one cycle were obtained from the total values of the right and left pole and leg thrust, respectively. The absolute peak force and time to peak force were determined on the basis of the pole and leg kinetics, respectively, and relative peak force (% of BW) was calculated by dividing the absolute force by the skier's body weight. The relative times to peak pole and leg forces were calculated by dividing the time to attain the maximal value by the total poling or leg thrust time, respectively. The rate of force development was obtained by dividing the peak force by the time required to achieve this peak.

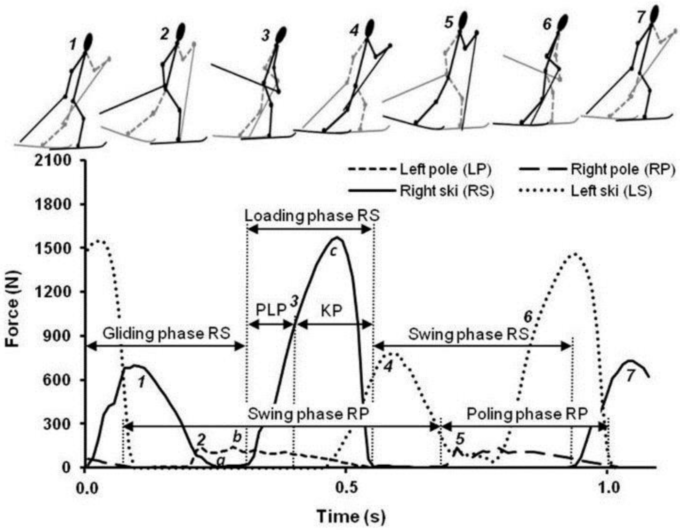

Figure 6. Sequence of actions (#1–7) and time course of pole and leg force characteristics associated with the diagonal stride skiing sub-technique over one cycle. *a* = unloading phase (leg force minima); *b* = peak pole force; *c* = peak leg force; PLP, pre-loading phase; KP, kick phase. Data are presented for one subject skiing at high velocity and are mean values of five successive time normalised cycles.

In *Study III* propulsive forces provided by the poles and leg thrust were estimated. The force impulse over a single cycle was time normalised by dividing the force impulses for poling (IPF) and leg thrust (ILF) for the two sides of the body by CT to obtain the average cycle pole force (ACPF) and average cycle leg force (ACLF) generated over one second. Then, the average cycle total force generated by pole and leg thrusts could be calculated as the sum of ACPF and ACLF. For estimation of the propulsive force provided by the poles ($ACPF_P$; eq. 1), the average sagittal and lateral angles between the poles at the time of plant and pole off were employed as follows:

$$ACPF_P[N] = (cos(\alpha) \times ACPF) \times sin(\beta) \qquad (1)$$

where α is the average lateral pole inclination and β the average sagittal pole inclination during the poling phase (Fig. 7A). These angles are not constant and the instantaneous angle and force should actually be considered and is hence a limitation of the current procedure.

The propulsive force of the leg thrust could not be evaluated in a similar manner, since the Pedar system does not provide information concerning force direction. However, when a skier moves at a constant velocity, this propulsive force is equal in size, but opposite in direction to the gravitational force component along the slope. Therefore, to obtain an average cycle propulsive leg force ($ACLF_P$; eq. 2), the following equation was applied:

$$ACLF_P[N] = (m \times g \times sin(\gamma)) - ACPF_P \qquad (2)$$

where m × g × sin(γ) is the gravitational force component along the slope, with m representing the mass of the skier's body, g gravitational acceleration and γ the incline. This formula does not take into account the force exerted against ground friction and air drag, which, in studies on similar types of locomotion such as running and walking on steep uphill terrain, are also routinely excluded from calculations (Minetti et al., 2002).

In *Study III* the average of the angles of the right and left poles at the start (defined as the first frame of pole-ground contact) and end (the last frame of pole-ground contact) of the poling phase during each cycle was calculated. The sagittal and lateral pole angles were defined as illustrated in Figure 7A and lateral angulation of the skis as the average angle between the left and right skis during their contact with the ground. The angles between body segments were calculated at the start and end of the right ski being in contact with the ground (see Fig. 7B). Inclination of the whole body, upper body, thigh and shank in the sagittal plane with respect to the ground was determined as were the angles of the hip and knee in the sagittal plane.

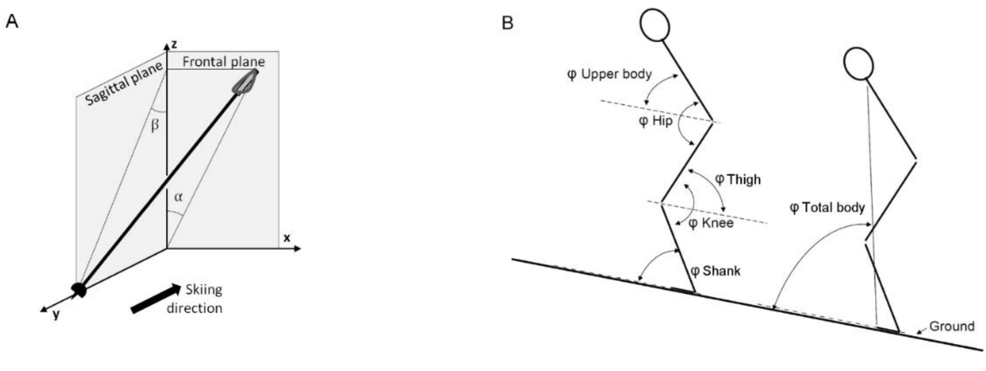

Figure 7. (A) Illustration of the sagittal (β) and lateral (α) pole angles. The y-coordinate is in the skiing direction, the x-coordinate is in the lateral plane which is perpendicular to the skiing direction and the z-coordinate is perpendicular to the slope; (B) Body segment and joint angles.

In *Studies IV* and *V* the power output (PO) during skiing was calculated as the sum of the power exerted to elevate the total mass against gravity and to overcome rolling resistance

$$PO\ [W] = m_{tot} \times g \times sin(\gamma) \times v + \mu_R \times m_{tot} \times g \times cos(\gamma) \times v. \tag{3}$$

Where m_{tot} is the skier's body mass together with equipment mass, g is gravitational accelerations, v is the treadmill velocity [m/s], μ_R is the rolling resistance coefficient and γ is the treadmill incline. The aerobic metabolic rate was determined from $\dot{V}O_2$ [L/min] and $\dot{V}CO_2$ and gross energy expenditure using RER values ≤ 1.00 (McArdle et al., 2010). Gross efficiency was calculated as PO divided by aerobic metabolic rate (J/s) and energetic cost (J/kg/m) as aerobic metabolic rate (J/s) divided by m_{tot} (kg) and velocity (m/s).

The calculations used to estimate the anaerobic energy supply in *Studies IV* and *V* were based on the submaximal relationships for skiing velocity and incline versus GE. These relationships were assessed with linear or exponential regression as based on the highest r^2 value and used to estimate the GE in the respective sub-techniques (DP and DS) during the supramaximal STT. The relationship between GE and velocity (v) or incline (i) in DP and DS was defined as either independent if $r^2 < 0.5$ and dependent if $r^2 \geq 0.5$. If velocity dependency was observed, the equation of the linear regression was used for prediction as

$$GE_v = GE(v). \tag{4}$$

If GE was shown to be independent of velocity, the average GE during the submaximal tests was applied. When incline dependency was observed the equation of the regression was used for prediction as

$$GE_i = GE(i). \tag{5}$$

The values obtained from eq. 5 were then divided by the GE_i at the fixed sectional inclines of 1° and 7°, respectively, resulting in the following ratio

$$GE_{i\ (ratio)} = GE_i \div GE_{i\ (1°\ or\ 7°)}. \tag{6}$$

If GE was shown to be independent of incline, the $GE_{i\ (ratio)}$ was set to 1 (i.e., no effect of incline on GE).

By combining eq. 4 and 6, a velocity and incline-dependent GE relationship (GE_{vi}) could be expressed as

$$GE_{vi} = GE_v \times GE_{i\ (ratio)}. \tag{7}$$

The total metabolic rate (MR) during the STT was calculated as

$$MR\ [W] = PO \div GE_{vi} \tag{8}$$

where PO is the STT power output (eq. 3), GE_{vi} is the supramaximal GE (eq. 7). The total MR was converted to a VO_2 requirement and the accumulated O_2 deficit was calculated as the difference between the VO_2 requirement and VO_2 uptake.

The V_{max} during the incremental tests (*Studies IV* and *V*) was linearized by using a similar equation to that introduced by Kruipers et al. (1985).

$$V_{max}\,[m/s] = V_f + (t \div T \times V_d) \tag{9}$$

where V_f is the velocity [m/s] of the last workload completed, t is the duration [s] of the last workload, T is the standard duration [s] of the workload and V_d is the difference in velocity [m/s] between the last two workloads.

3.6. STATISTICS

In all studies, all data were checked for normality and presented as mean and standard deviation (± SD) with some variables presented as median and/or range. The coefficient of variation (100 × SD / mean) was used as a measure of relative variability in *Studies I, IV* and *V*. Mean values were compared with a paired sample t-test (*Studies I, IV*), independent sample t-test (*Study IV*), one-way ANOVA (*Study I*), one-way repeated measures ANOVA (*Studies II-V*) and two-way ANOVA (*Studies IV* and *V*). Relationships between variables were assessed with the Pearson's correlation analysis (*Studies I, IV* and *V*) and linear or exponential regressions (*Studies IV* and *V*). A block-wise multiple regression was used to determine the explained variance in performance for the selected independent variables (*Studies IV* and *V*). When data deviated from a normal distribution the following non-parametric alternatives were used: Wilcoxon signed-rank test (*Study I*), Mann-Whitney U test (*Study II*) and Spearman's rho rank correlation (*Study I*). In all studies, the level of statistical significance was set at $\alpha \leq 0.05$. Statistical tests were processed using Office Excel 2006, 2007 or 2010 versions (Microsoft Corporation, Redmond, WA, USA) and SPSS 17.0 (SPSS Inc., Chicago, IL, USA) or SPSS 21 (IBM Corp., Armonk, NY, USA). The statistical methods are described further in detail in the separate articles.

4. RESULTS

4.1. STUDY I

Nine male elite c.c. skiers performed a V_{max} test using G3 (G3-V_{max}) and a maximal acceleration test in DP (DP-V_{peak}), followed by a skating STT (sub-techniques are illustrated in Fig. 8).

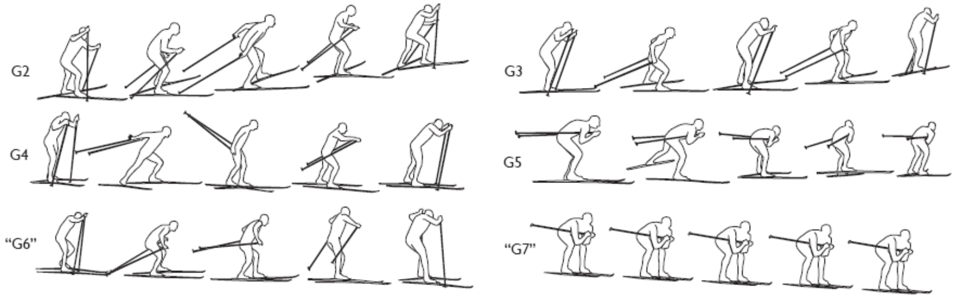

Figure 8. Schematisation of the different skating sub-techniques (gears [G2-7]) used in c.c. skiing. G2, G3, and G4 is sometimes termed V1, V2, and V2-alternate, respectively.

The maximal velocities reached in the DP-V_{peak} (20 m) and G3-V_{max} (120 m) tests were 7.87 ± 0.36 m/s (28.3 ± 1.3 km/h) and 10.21 ± 0.41 m/s (36.8 ± 1.5 km/h), respectively. The time to complete the STT was 207.4 ± 7.4 s, with an average velocity of 6.9 ± 0.3 m/s (24.8 ± 1.1 km/h). The velocity profile over the STT course is shown in Figure 9.

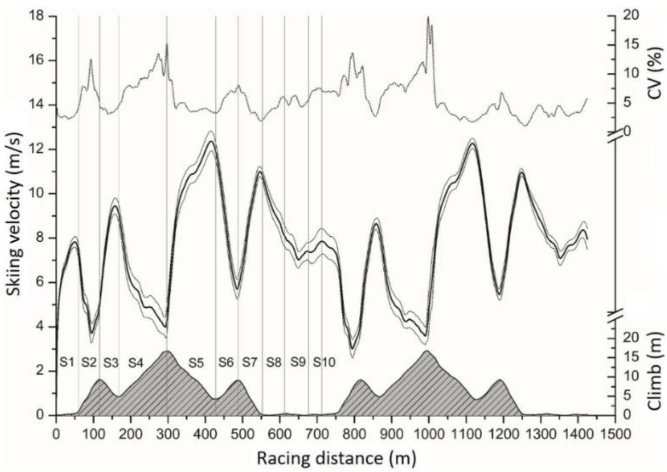

Figure 9. The 1,425-m sprint time trial course profile (grey area under the curve), skiing velocity (solid line; *mean* ± *SD*), and coefficient of variation (CV) (dashed upper line) plotted against racing distance (m) for both laps. The vertical lines represent all the sections (S1-10) of one lap.

The STT encompassed a large velocity range (2.9-12.8 m/s [10.4-46.1 km/h]) with the highest inter-individual variation (i.e., CV) observed for the uphill skiing velocity. The average velocity for G3 skiing during the final stretch (20 m) before the finish line corresponded to ~ 80% of G3-V_{max}. The average velocities for the three different categories of terrain (i.e., uphill, downhill and flat) are shown in Figure 10A. During the STT, 29.1 ± 4.0 gear transitions were performed and higher gears were used at higher velocities (Fig. 10B).

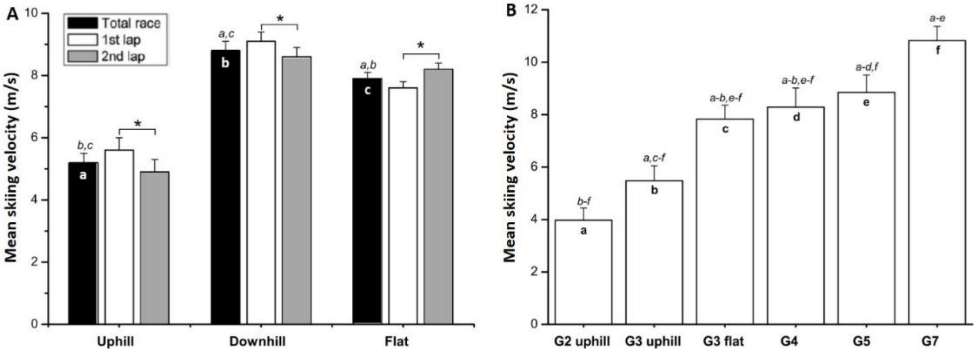

Figure 10. (A) Mean skiing velocities for different categories of terrain (uphill, downhill and flat): during the total race, 1st and 2nd laps; (B) Mean skiing velocities for the skating sub-techniques (G2-7). The different letters indicate significant differences between terrain (Fig. A [a-c]) and gears (Fig. B [a-f]), and * indicates a significant difference between laps, $P < 0.05$. Values expressed as *mean* ± *SD*.

The first lap of the STT was 2.9% faster than the second lap (102.1 ± 3.7 versus 105.2 ± 4.4 s; $P < 0.05$). The average velocities over the second lap were 12.9% and 5.3% slower for the uphill and downhill sections, respectively, whereas the skiers were 7.6% faster over the flat sections (Fig. 10A). The distribution of the main skating gears, G2-4, were on average 31%, 63% and 6%, respectively. The slower uphill velocities over the second lap were associated with a shift in gear choice towards less use of G3 (- 6.8%) and larger use of G2 (+ 5.9%) ($P < 0.05$).

The STT performance time was highly correlated to uphill time ($r = 0.92$, $P < 0.05$). The reduction in uphill velocity on the second lap was negatively correlated with the pre-determined $\dot{V}O_{2max}$ ($r = -0.78$, $P < 0.05$). There was a negative correlation between STT performance time and DP-V_{peak}, as well as for the total time spent on the uphill sections ($r = -0.71$ and $r = -0.73$, both $P < 0.05$). The time used on the steepest uphill section (S2) during both laps was negatively correlated with DP-V_{peak} (first and second laps: $r = -0.79$, and $r = -0.84$, both $P < 0.05$), and DP-V_{peak} correlated positively with the skiers' percentage of racing time using G3 and negatively with the skiers' time using G2 ($r = 0.71$ and $r = -0.83$, respectively, both $P < 0.05$).

4.2. STUDY II

This study examined cycle and force characteristics in eleven elite male c.c. skiers using the DS sub-technique while skiing uphill (7.5°) on snow at moderate, high and maximal velocities.

Absolute cycle, poling, arm swing, gliding, kick, and leg swing times decreased significantly with an elevated velocity (Table 2). The relative phases remained constant from moderate to high velocity, whereas the relative glide, the relative kick and leg swing times were prolonged from high to maximal velocity (Table 2). The cycle rate and cycle length increased from moderate to high velocity, while cycle rate increased and cycle length decreased at maximal velocity (Fig. 11A).

Table 2. Cycle and force characteristics of diagonal skiing at moderate, high and maximal velocity.

	Velocity		
	Moderate	High	Maximal
Velocity (km/h)	12.6 ± 1.1	16.2 ± 1.4	20.2 ± 2.2
Cycle time (s)	1.15 ± 0.07^{bc}	1.01 ± 0.10^{ac}	0.69 ± 0.09^{ab}
Poling time (s)	0.45 ± 0.07^{bc}	0.38 ± 0.04^{ac}	0.27 ± 0.03^{ab}
AST (s)	0.70 ± 0.04^{bc}	0.63 ± 0.09^{ac}	0.41 ± 0.07^{ab}
Gliding time (s)	0.42 ± 0.05^{bc}	0.36 ± 0.08^{ac}	0.19 ± 0.07^{ab}
PLT (s)	0.07 ± 0.01	0.06 ± 0.01	0.05 ± 0.01
Kick time (s)	0.19 ± 0.03^{bc}	0.16 ± 0.02^{ac}	0.14 ± 0.02^{ab}
LST (s)	0.47 ± 0.06^{bc}	0.43 ± 0.06^{ac}	0.32 ± 0.05^{ab}
PT_{rel} (%)	39 ± 4	38 ± 4	40 ± 3
AST_{rel} (%)	61 ± 4	62 ± 4	60 ± 3
GT_{rel} (%)	36 ± 3^{c}	36 ± 5^{c}	27 ± 8^{ab}
PLT_{rel} (%)	6 ± 1	6 ± 1	7 ± 1
KT_{rel} (%)	17 ± 2^{c}	16 ± 2^{c}	20 ± 2^{ab}
LST_{rel} (%)	41 ± 5^{c}	43 ± 5^{c}	46 ± 7^{ab}
PPF (N)	100 ± 24^{bc}	118 ± 36^{ac}	197 ± 44^{ab}
PLF (N)	1531 ± 217	1538 ± 184	1448 ± 187
RFD_{pole} (kN/s)	1.0 ± 0.9^{bc}	1.6 ± 1.5^{ac}	5.8 ± 1.5^{ab}
RFD_{leg} (kN/s)	10.1 ± 2.4^{bc}	12.6 ± 2.3^{ac}	13.9 ± 2.4^{ab}
IPF (Ns)	22 ± 4^{c}	22 ± 5^{c}	18 ± 2^{ab}
ILF (Ns)	235 ± 39^{c}	215 ± 27^{c}	174 ± 21^{ab}

Values presented as *mean* ± *SD* (*n* = 11). AST, arm swing time; PLT, pre-loading time; LST, leg swing time; PT_{rel}, relative poling time; AST_{rel}, relative arm swing time; GT_{rel}, relative glide time; PLT_{rel}, relative pre-loading time; KT_{rel}, relative kick time; LST_{rel}, relative leg swing time. PPF, peak pole force; PLF, peak leg force; RFD_{pole}, rate of force development for poling; RFD_{leg}, rate of force development for the leg during the ski-loading phase; IPF, impulse of pole force; ILF, impulse of leg force. The letters indicate statistically significant differences from moderate (*a*), high (*b*) or maximal (*c*) velocity ($P < 0.05$).

The relative pole forces increased considerably from moderate to maximal velocity (13% to 26% of BW), while the time to peak pole force decreased by 79% (Fig. 11B). The relative leg force was unchanged across velocities (~ 190% of BW), while time to peak leg force decreased by 26% from moderate to maximal velocity (Fig. 11C). During gliding, most of the force was distributed on the inside rear-foot, with a distinct shift of loading to the inside forefoot during the kick (Fig. 11D).

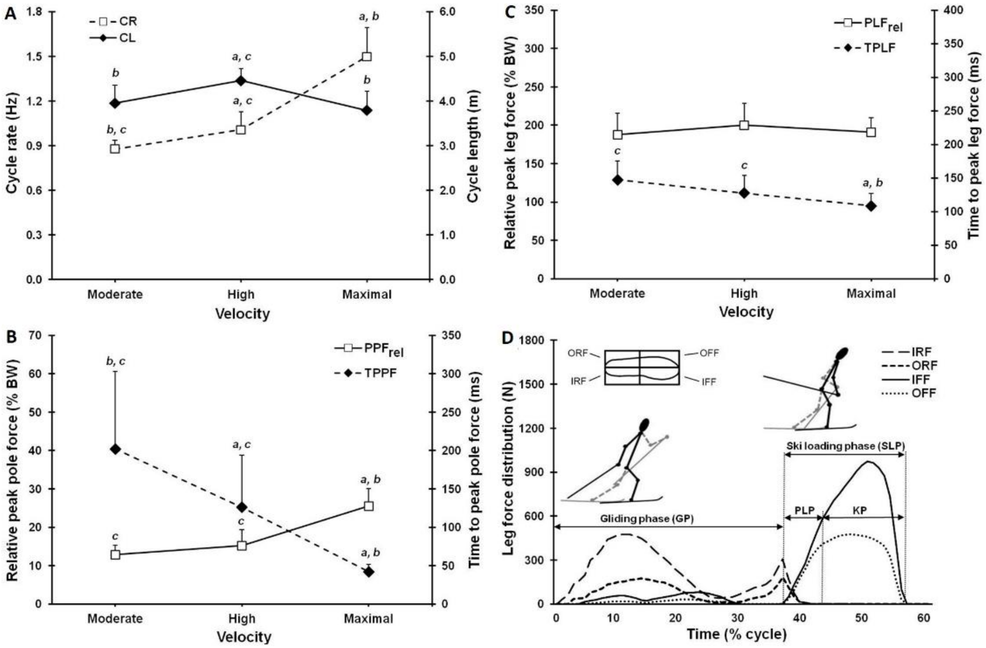

Figure 11. (A) Cycle rate (CR) and cycle length (CL); (B) relative peak pole force (PPF_{rel}) and time to peak pole force (TPPF); (C) Relative peak leg force (PLF_{rel}) and time to peak leg force (TPLF), at three different diagonal skiing velocities (*mean* ± *SD* [*n* = 11]); (D) Force distribution on inside rear-foot (IRF), outside rear-foot (ORF), inside forefoot (IFF) and outside forefoot (OFF), for one participant skiing at high velocity; PLP, pre-loading phase; KP, kick phase. The letters indicate statistically significant differences from moderate (*a*), high (*b*) or maximal (*c*) velocity ($P < 0.05$).

At maximal velocity, sprint-specialised skiers were 14% faster than distance-specialised skiers (22.4 vs. 19.7 km/h), attributed to a higher cycle rate (1.64 vs. 1.34 Hz), a shorter poling time (0.26 vs. 0.30 s), glide time (0.17 vs. 0.24 s), and kick time (0.13 vs 0.15 s) (all $P < 0.05$). The sprint-specialised skiers developed a higher peak leg force (195 vs. 176 % of BW), and a higher rate of leg force development (14.1 vs. 11.9 kN/s) than the distance skiers (both $P < 0.05$).

4.3. STUDY III

Eleven elite male c.c. skiers performed HB skiing on a steep uphill (15°) at maximal (13.7 ± 1.4 km/h), high (10.8 ± 1.4 km/h) and moderate (8.6 ± 1.4 km/h) velocities. A schematic illustration of the HB sub-technique performed at high velocity, with the corresponding kinetic and kinematic characteristics of a representative individual skier, is presented in Figure 12.

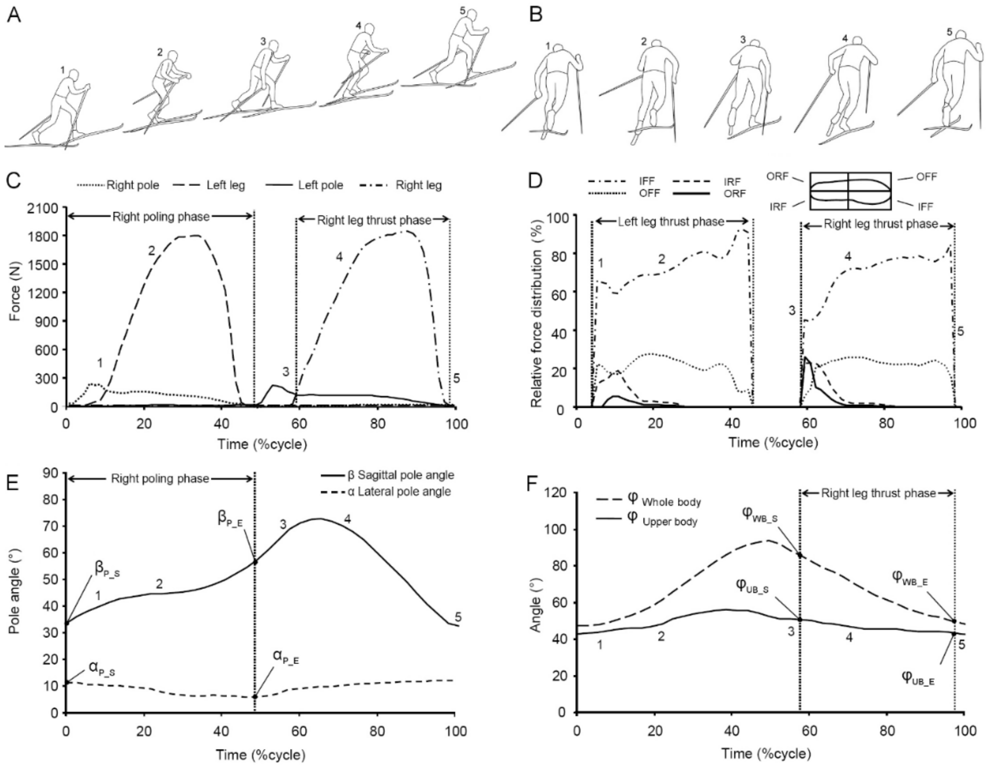

Figure 12. Kinetic and kinematic characteristics of an individual skier during one cycle of the herringbone sub-technique performed at high velocity. The numbers (1-5) on all graphs represent the different phases of the cycle (side view [A] and back view [B]); (C) Time course of the pole and leg thrust forces; (D) Relative distribution of the force (as % of the total force) between the inside forefoot (IFF), outside forefoot (OFF), inside rearfoot (IRF) and outside rearfoot (ORF); (E) Lateral and sagittal pole angles; (F) Upper and total body angles (see Fig. 7A for definition of angles).

The cycle rate increased with velocity, being 1.20 ± 0.08, 1.31 ± 0.08, and 1.60 ± 0.14 Hz at the moderate, high, and maximal velocities, respectively, whereas the cycle length increased from moderate up to high velocity (2.04 ± 0.23 to 2.31 ± 0.23 m), with no further change up to maximal velocity (2.34 ± 0.22 m). The absolute poling and leg thrust times gradually decreased with higher velocity, while relative poling and leg thrust times were independent of velocity (Fig. 13A-B).

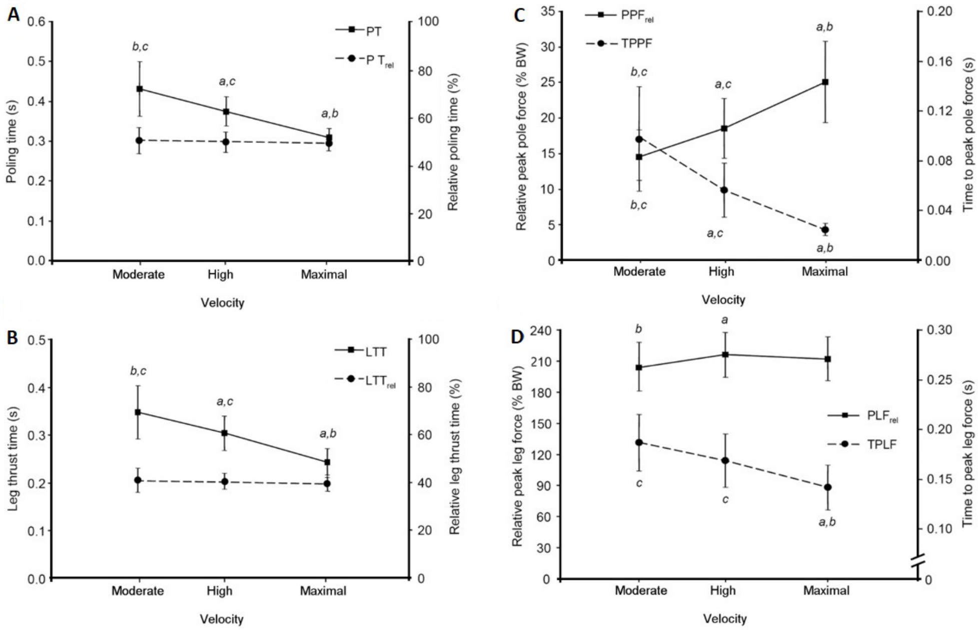

Figure 13. (A) Absolute and relative poling times (PT and PT_{rel}); (B) Absolute and relative leg thrust times (LTT and LTT_{rel}); (C) Relative peak pole force (PPF_{rel}) and time to peak pole force (TPPF); (D) Relative peak leg force (PLF_{rel}) and time to peak leg force (TPLF) for herringbone skiing at three different velocities. The values presented are *means* ± *SD* (n = 11). The letters indicate significant differences in comparison to moderate (*a*), high (*b*) or maximal (*c*) velocity ($P < 0.05$).

Force characteristics across the three different velocities of HB skiing are documented in Table 3. The relative peak pole force increased 74% from moderate to maximal velocity, while the time to peak pole force declined by 75% (Fig. 13C). The relative peak leg force was increased by 7% from moderate to high velocity, with no further change from high to maximal velocity. The time required to attain peak leg force was 24% lower at maximal than at moderate velocity (Fig. 13D).

As documented in Table 3, the higher peak force and the shorter time required to attain this force resulted in an almost 4-fold increase in the rate of force development by the poles from moderate to maximal velocity, with only a 38% increase for the leg thrust. The pole and leg force impulses remained relatively constant across velocities upon increasing from moderate to high velocity and then fell at maximal velocity.

The leg force impulse was mainly (66%) distributed on the inside forefoot at all three velocities. The average pole and leg forces per movement cycle were independent of velocity. The average relative propulsive pole and leg forces per cycle were ~ 71% and 20%, respectively, at all velocities. Of the total propulsion, pole and leg forces contributed with ~ 23% and 77%, respectively.

Table 3. Force characteristics associated with skiing with the herringbone sub-technique at three different velocities.

	Velocity		
	Moderate	High	Maximal
PPF (N)	112 ± 24[bc]	143 ± 32[ac]	194 ± 43[ab]
PLF (N)	1530 ± 240[b]	1640 ± 216[a]	1610 ± 234
RFD_{pole} (kN/s)	2.28 ± 1.29[bc]	4.03 ± 1.74[ac]	8.74 ± 2.81[ab]
RFD_{leg} (kN/s)	8.45 ± 2.09[bc]	10.10 ± 2.46[ac]	11.70 ± 2.25[ab]
IPF (Ns)	52 ± 5[c]	49 ± 7[c]	42 ± 7[ab]
ILF (Ns)	653 ± 133[c]	617 ± 103	505 ± 102[a]
ACPF (N)	62 ± 7	64 ± 9	67 ± 13
ACLF (N)	774 ± 153	808 ± 133	807 ± 149
$ACPF_P$ (N)	44 ± 5	45 ± 6	47 ± 8
$ACLF_P$ (N)	160 ± 23	155 ± 17	153 ± 17
$ACPF_{P\_rel}$ (%)	71 ± 1	71 ± 2	70 ± 3
$ACLF_{P\_rel}$ (%)	21 ± 4	19 ± 3	19 ± 3
FI_{P_ratio} (%)	29 ± 5	30 ± 4	31 ± 6

Values presented as *mean* ± *SD* (n = 11). PPF (N), peak pole force; PLF (N), peak leg force; $TPPF_{rel}$ (%), relative time required to attain peak pole force; $TPLF_{rel}$ (%), relative time required to attain peak leg force; RFD_{pole} ($N·s^{-1}$), rate of development of pole force; RFD_{leg} ($N·s^{-1}$), rate of development of leg force; IPF (Ns), Impulse of the pole force; ILF (Ns), impulse of the leg force; ACPF (N), average pole force per cycle; ACLF (N), average leg force per cycle; $ACPF_P$ (N), average propulsive pole force per cycle; $ACLF_P$ (N), average propulsive leg force per cycle; $ACPF_{P\_rel}$ (%), average relative propulsive pole force per cycle; $ACLF_{P\_rel}$ (%), average relative propulsive leg force per cycle; FI_{P_ratio} (%), ratio of the propulsive pole to leg force impulse. The letters indicate significant differences in comparison to moderate (a), high (b) and maximal (c) velocities ($P < 0.05$).

4.4. STUDY IV

Eleven male c.c. skiers were tested on a treadmill in the laboratory for determination of GE, $\dot{V}O_{2max}$, and V_{max}. The main performance test involved four self-paced STTs over a 1,300-m simulated sprint course on the treadmill including three flat (1°) DP sections interspersed with two uphill (7°) DS sections (see Fig. 15A for details).

The relationships between skiing velocity and GE in DP and DS are shown in Figure 14. Although no significant influence of velocity on GE was observed (Fig. 14A), five skiers demonstrated a linearly decreasing GE against velocity (Skier A in Figure 14B was one of those). The relationship between GE and incline exhibited a slightly inverted u-shape for DP, but was linearly increasing in the case of DS (Fig. 14C). When expressed as an energetic cost plotted against incline at the same velocities as in Figure 14C, a cross-over in energetic cost for DP and DS was observed at 3.3° (Fig. 14D). The V_{max} in DP and DS were 32.8 ± 1.8 and 18.4 ± 1.1 km/h, respectively.

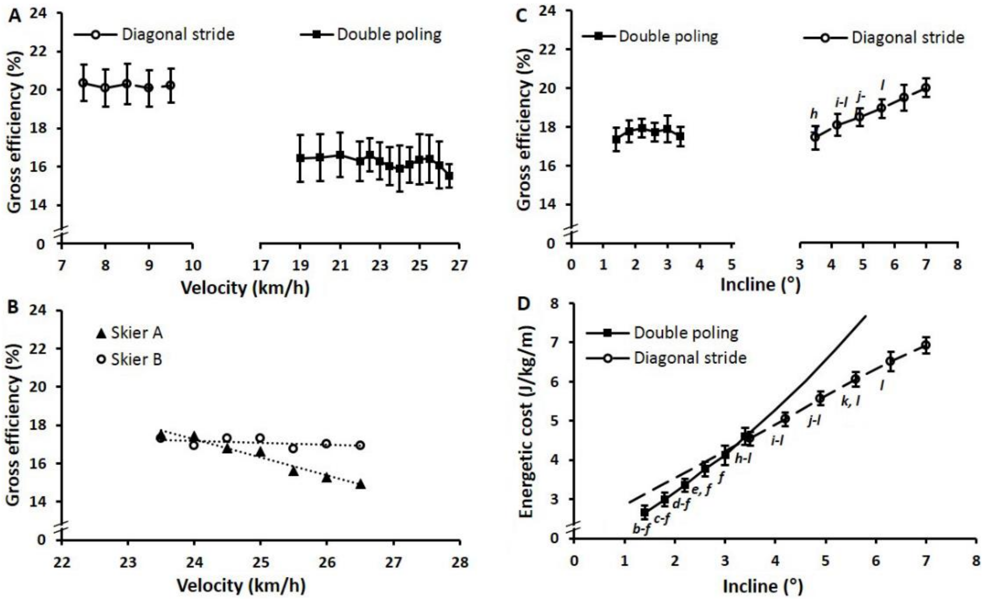

Figure 14. (A) Gross efficiency for submaximal double poling (DP) and diagonal stride (DS) at fixed inclines of 1° (DP) and 7° (DS), plotted against skiing velocity; (B) Two individual relationships between gross efficiency and DP velocity; (C) Gross efficiency for submaximal DP and DS treadmill roller skiing at fixed velocities of 16.0 and 9.5 km/h, respectively, plotted against incline; and (D) Energetic cost plotted against incline at the same velocities as in (C), including upward and downward trend lines. The values are presented as *mean* ± *SD* (Fig. A, C-D). The letters indicate statistically significant differences between the six stages of skiing with DP (*a-f*) and DS (*g-l*).

The skiers completed the STT in 232 ± 10 s (distributed as 55 ± 3% DP and 45 ± 3% DS) with an average velocity of 20.2 ± 1.1 km/h, power output of 324 ± 26 W, and metabolic rate of 1.87 ± 0.18 kW. The aerobic and anaerobic energy contributions were 82 ± 5% and 18 ± 5%, respectively, with an accumulated O_2 deficit of 45 ± 13 mL/kg. The peak $\dot{V}O_2$ of 5.20 ± 0.48 L/min did not differ significantly from the highest $\dot{V}O_{2max}$ value of 5.14 ± 0.48 L/min attained with DP or DS skiing during the pre-tests. The blood lactate concentrations 1-min before and immediately after the STT were 3.6 ± 1.0 and 12.8 ± 1.9 mmol/L, respectively.

The physiological and biomechanical parameters observed for each of the five different sections are documented in Figure 15 and Table 4. The highest variations in skiing velocity (as reflected in the coefficient of variation [CV]) were observed in connection with the start of the two uphill sections involving DS (S2 and S4) (Fig. 15A). An increased O_2 deficit was detected in S1, S2 and S4 combined with a slightly reduced O_2 deficit in S3 and S5 (Fig. 15B-D). The mean metabolic rate for all three DP sections was 23% lower than for the two DS sections (1.7 ± 0.3 versus 2.2 ± 0.1 kW; $P < 0.05$).

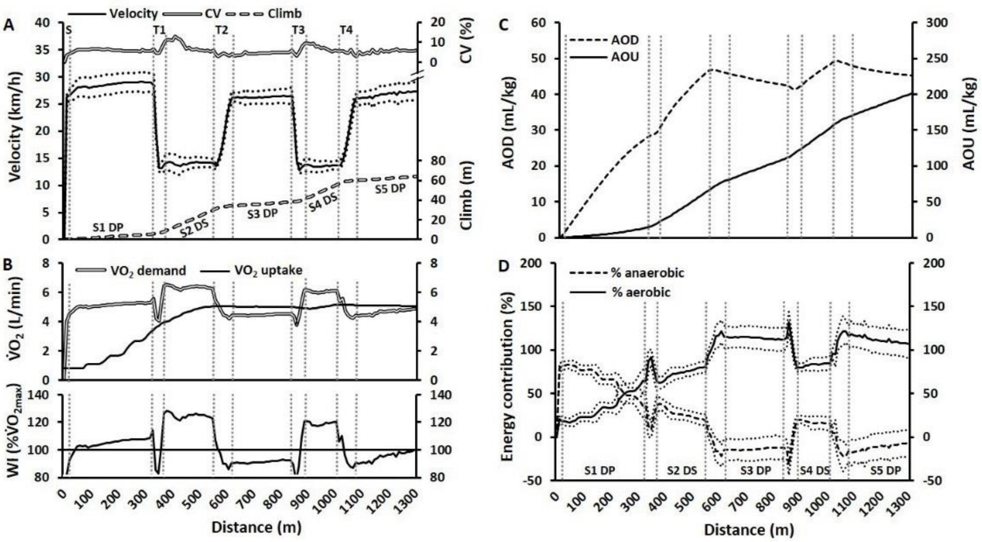

Figure 15. (A) Skiing velocity, coefficient of variation and vertical climb. The vertical lines represent the three double poling (DP) course sections (S1, S3 and S5 at a 1° incline) and the two diagonal stride (DS) sections (S2 and S4 at a 7° incline) together with the start-up (S) and the four transition phases (T1-T4); (B) O_2 demand, $\dot{V}O_2$ and relative work intensity (WI) in percent of $\dot{V}O_{2max}$; (C) accumulated O_2 uptake (AOU) and O_2 deficit (AOD); (D) relative energy system contributions plotted against skied distance. The values presented are an average of four sprint time trials and are presented as *mean* ± *SD*, except for Figures B and C where only means where presented.

Block-wise multiple regression revealed that GE, $\dot{V}O_2$ and O_2 deficit explained 53.4%, 30.1%, 15.2% of the total variance in STT performance time, respectively (all contributions $P < 0.05$). None of the three pair-wise correlations between STT time and GE, $\dot{V}O_2$ and O_2 deficit were statistically significant. The V_{max} in DP and DS were negatively correlated to the respective DP and DS total section times (r = - 0.79 and - 0.56, both $P < 0.05$).

Table 4. Biomechanical and physiological results for the five sections (S1-5) of the 1,300-m skiing time trials.

	S1 (DP)	S2 (DS)	S3 (DP)	S4 (DS)	S5 (DP)
Velocity (km/h)	28.1 ± 1.8^{c,e}	14.0 ± 0.7*	25.9 ± 1.1	13.3 ± 0.7	26.3 ± 1.1
Cycle rate (Hz)	1.01 ± 0.10^{e}	0.88 ± 0.04*	0.97 ± 0.08^{e}	0.86 ± 0.04	1.09 ± 0.10
Cycle length (m)	7.7 ± 0.8^{c,e}	4.5 ± 0.3*	7.4 ± 0.5^{e}	4.3 ± 0.3	6.7 ± 0.3
Power output (W)	255 ± 27^{c,e}	445 ± 32*	236 ± 20	430 ± 31	240 ± 22
Metabolic rate (W)	1796 ± 358^{b,c,e}	2204 ± 121^{c,d,e}	1577 ± 247^{d}	2131 ± 139^{e}	1633 ± 288
GE (%)	15 ± 2	20 ± 1	15 ± 1	20 ± 1	15 ± 2
VO_{2req} (mL/kg)	39 ± 5	60 ± 3	27 ± 3	39 ± 2	28 ± 3
VO_2 (mL/kg)	13 ± 1	44 ± 3	31 ± 1	33 ± 2	31 ± 2
AOD (mL/kg)	26 ± 5	16 ± 3	-3 ± 3	7 ± 2	-3 ± 3
$\dot{V}O_{2max\_FU}$ (%)	35 ± 3	91 ± 5	102 ± 3	99 ± 4	104 ± 2

The values are presented as *mean* ± *SD* (*n* = 11) and are an average of four time trials. Abbreviations: DP, double poling; DS, diagonal stride; GE, gross efficiency; VO_{2req}, required oxygen uptake; VO_2, accumulated oxygen uptake; AOD, accumulated oxygen deficit; $\dot{V}O_{2max\_FU}$, fractional utilisation of maximal oxygen uptake. Significantly different from S1 (a), S2 (b), S3 (c), S4 (d) or S5 (e) ($P < 0.05$), *significantly different from S4 ($P < 0.05$). No statistical comparisons were performed for all the variables below metabolic rate.

As based on velocity and incline, the energetic cost at the four transition points (T1 and T3, DP to DS; T2 and T4, DS to DP) were similar between DP and DS at T1 and T3 (~ 4.0 ± 1.2 J/kg/m). In contrast when changing from DS to DP at T2 and T4 the energetic cost for DP was considerably higher than for DS (5.7 ± 1.1 versus 5.3 ± 0.7 J/kg/m and 6.1 ± 1.0 versus 5.4 ± 0.6 J/kg/m, respectively) resulting in main effects between transitions and sub-techniques as well as an interactive effect between these (all $P < 0.05$).

4.5. STUDY V

Ten well-trained male c.c. skiers performed four 1,300-m STTs on a treadmill, each separated by 45 min of recovery (same STT course as in *Study IV*, see Fig. 16A). Preliminary testing was performed similarly as in *Study IV*.

Performance, mechanical and physiological responses to the four STTs, together with statistical comparisons, are presented in Table 5. The peak $\dot{V}O_2$ in each respective STT was similar to the highest $\dot{V}O_{2max}$ of 62.2 ± 6.0 mL/kg/min observed in the incremental pre-tests. The velocity profiles for the two fastest and slowest STTs in relation to the average STT velocity are presented in Figure 16B. It can be noted that the most aggressive pacing strategy was utilised in STT1. The skiers' work intensities were highest on the two uphill DS sections (~ 118-128% of DS $\dot{V}O_{2max}$ on S2 and S4) and slightly below their DP $\dot{V}O_{2max}$ on the final two DP sections (~ 90-100%

of DP $\dot{V}O_{2max}$ on S3 and S5), with a decrease in O_2 deficit on S3 and S5 (Fig. 16C-D). The individually fastest and slowest STTs were completed in 225 ± 10 s and 233 ± 10 s, respectively ($P < 0.05$), this superior performance in the fastest STT was reflected by a more aggressive pacing with a higher power output (~ 5%) during the first two sections of the course (Fig. 16E).

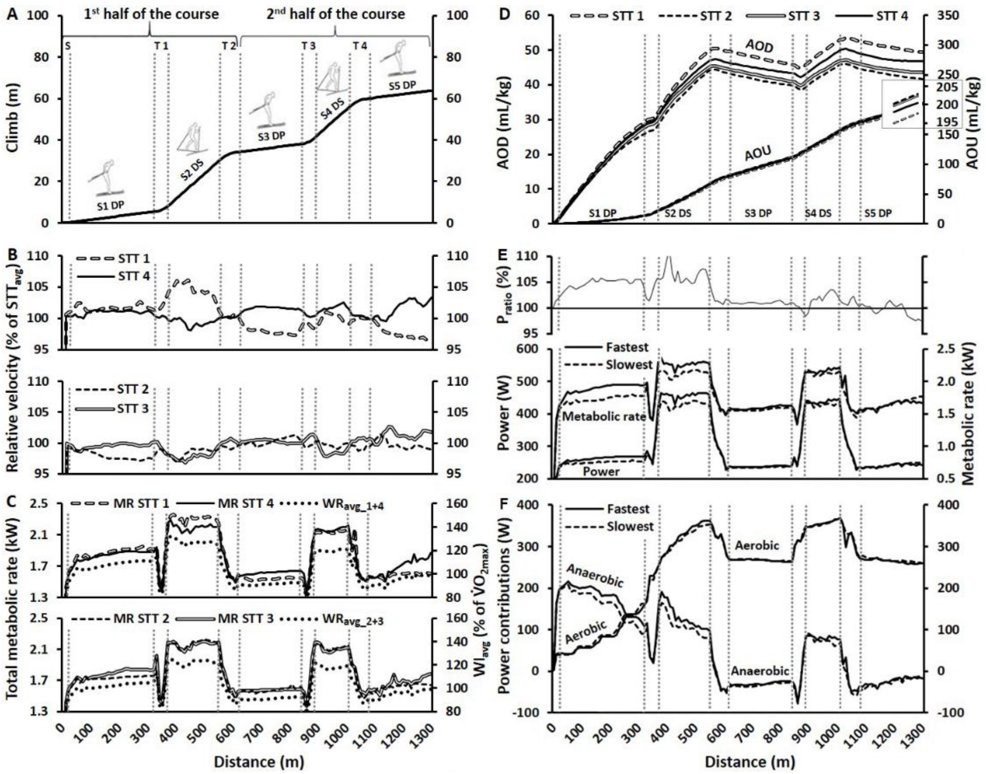

Figure 16. (A) The sprint time trial (STT) course profile. (B) Relative velocity as a percentage of the average velocity for all four STTs (% of STT_{avg}) for the two fastest (STT1 and 4: 228 s) and slowest (STT2, 231s; STT3, 230 s) STTs; (C) The metabolic rate (MR) for the respective trials and the average work intensity (WI_{avg}) in percent of $\dot{V}O_{2max}$ for the two fastest and slowest STTs; (D) Accumulated O_2 uptake (AOU) and O_2 deficit (AOD) during the four STTs; (E) Ratio between power output during the individually fastest and slowest STTs (P_{ratio}) and absolute power output and metabolic rate during the two respective STTs; (F) Aerobic and anaerobic contributions to power output. The inserted square shows a magnification of the AOU over the last 30 m. The data are presented as *mean* values.

The CV for individual trial-to-trial variability in STT time, $\dot{V}O_2$ and O_2 deficit (both expressed in mL/kg/min) were 1.3 ± 0.4%, 1.4 ± 0.9% and 11.2 ± 4.9%, respectively. In addition, trial-to-trial variations in O_2 deficit and $\dot{V}O_2$ explained 69% ($P < 0.05$) and 11% ($P > 0.05$), respectively, of the individual variation in STT performance.

Table 5. Performance during four repeated 1,300-m sprint time trials (STT1-4) and the associated mechanical and physiological responses.

	STT1	STT2	STT3	STT4
Time (s)	228 ± 9^{b,c}	231 ± 10^{d}	230 ± 9^{d}	228 ± 9
Average velocity (km/h)	20.6 ± 0.8^{b,c}	20.3 ± 0.9^{d}	20.3 ± 0.8^{d}	20.6 ± 0.9
Average power output (W)	326 ± 27^{b,c}	321 ± 24^{d}	322 ± 26^{d}	326 ± 27
Average metabolic rate (kW)	1.89 ± 0.20^{b,c}	1.84 ± 0.17^{d}	1.86 ± 0.17^{d}	1.89 ± 0.19
Accumulated VO_2 (mL/kg)	197 ± 10^{b,c,d}	203 ± 10	202 ± 11	200 ± 10
Accumulated O_2 deficit (mL/kg)	49 ± 14^{b,c}	41 ± 11^{d}	43 ± 14^{d}	47 ± 13
Average $\dot{V}O_2$ (mL/kg/min)	52 ± 3	52 ± 3	53 ± 3	53 ± 3
Average O_2 deficit (mL/kg/min)	13 ± 4^{b,c}	11 ± 3^{d}	11 ± 4^{d}	12 ± 4
Anaerobic energy contribution (%)	20 ± 5^{b,c}	17 ± 4^{d}	17 ± 4^{d}	19 ± 5

Statistically significantly different from *b* = STT2, *c* = STT3, *d* = STT4 ($P < 0.05$). The values are presented as *mean* ± *SD*.

As shown in Figure 17A, the skiers employed positive pacing throughout all STTs as explained by the shorter time on the first half (H_1) than the second half (H_2). The absolute energy contributions on the first and second halves of the course for each of the four STTs are shown in Figure 17B. The average V_{max} (mean of V_{max} for DP and DS) was positively correlated to the time difference between H_2 and H_1 (using an average of the four STTs), i.e., the skiers with the highest V_{max} employed the most aggressive pacing strategies ($r = 0.66$, $P < 0.05$).

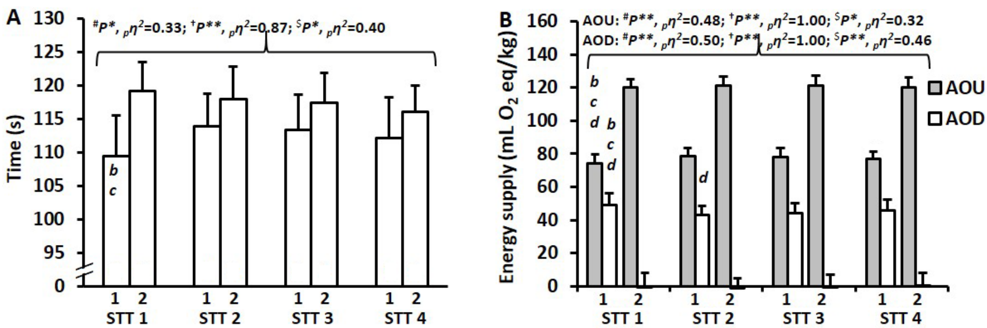

Figure 17. (A) Times spent on the first (1) and second (2) halves of the course for each of the four 1,300-m sprint time trials (STTs), (B) accumulated O_2 uptake (AOU) and O_2 deficit (AOD) on the two course halves. Statistically significantly different from *b* = STT2, *c* = STT3, *d* = STT4 ($P < 0.05$). #Main effect between STT1-4. †Main effect between the first and second halves of the course. $Interactive effect. P^* = $P < 0.01$ and P^{**} = $P < 0.001$. $_p\eta^2$ = partial eta effect size.

On average, the skiers covered the 740 m of DP skiing in 99 s and the 300 m of DS skiing in 79 s corresponding to velocities of 27.0 and 13.7 km/h or 81% and 73% of V_{max} for the respective sub-techniques. The metabolic rate was, on the average, 23%

lower during the flat DP compared to the uphill DS skiing (1.68 versus 2.18 kW). The ratio of the completed time using DS divided by DP in STT1-4 was on average 79 ± 4%, and was positively correlated to the skier's total mass (r = 0.67, P < 0.05).

5. DISCUSSION

The present thesis provides methodological advances as well as physiological and biomechanical insights into elite c.c. skiing performance. Measurements were conducted in the field on snow (*Studies I-III*) and during treadmill roller skiing in the laboratory (*Studies IV* and *V*). In *Study I*, a d-GNSS system combined with video recording were used for continuous evaluation of performance along a 1,425-m race course, revealing important knowledge about gear selection and pacing strategies in relation to overall sprint-skiing performance. *Studies II* and *III* were designed to analyse the effects of increasing velocity on the kinematics and kinetics of the DS and HB sub-techniques on snow, thus furthering our understanding of classical c.c. skiing on the steepest uphill sections of a course. In *Studies IV* and *V* a modified GE method was applied to estimate the anaerobic energy supply during STTs over a 1,300-m simulated treadmill course, which improved our understanding of the physiological determinants of sprint performance. Finally, *Study V* focused on the influence of self-selected pacing strategies on metabolic responses during four repeated STTs.

5.1. KINEMATICS

Study II demonstrated that regulation of velocity from high to maximal is mainly related to a substantially increased cycle rate at a shortened cycle length, which corroborate previous findings by Stöggl et al. (2011) who employed DS roller skiing at a similar incline. By contrast, previous studies examining velocity adaptations during DS on flat and slightly uphill (2.5°) terrains on snow have shown that increases in velocity are mainly associated with increases in cycle rate, with a nearly constant cycle length up to maximal velocity (Nilsson et al., 2004a; Vähäsöyrinki et al., 2008). This inconsistency may, at least in part, be related to differences in slope gradients, where the higher resistance due to gravity in the current study is likely to increase the importance of a high cycle rate for reducing velocity fluctuations (Hoffman et al., 1995).

The velocity of HB skiing (*Study III*) was mainly regulated by changes in cycle rate, with observed cycle rates of 1.19 to 1.61 Hz, exceeding those reported previously for DS at similar velocities, but lower inclines (Lindinger et al., 2009a; Stöggl & Müller, 2009). This difference probably reflects the additional resistance by gravity imposed by the steep incline, together with the lack of a gliding phase in HB. In comparison to steep uphill running at a similarly high velocity (Gottschall & Kram, 2005), the cycle length during HB was somewhat longer, most likely due to the additional propulsion provided by the poles. In DS, non-linear, concave upward and downward curves were observed for the cycle rate and cycle length adaptations across the three velocities, which is similar to the velocity adaptation in running (Hay, 2002). Hay (2002) demonstrated that the maximal cycle length during running was attained at a velocity corresponding to ~ 85% of the maximal velocity and a similar relationship was observed in *Study II*.

A comparison of the velocity adaptation characteristics between sprint- and distance-specialised skiers was made in *Study II.* The sprint-specialised skiers were 10% faster than the distance-specialised skiers at the high velocity due to their ability to generate longer cycle lengths. Furthermore, at maximal velocity the sprint-specialised skiers exhibited a more rapid cycle rate to compensate for a reduced cycle length and reached 14% higher velocities than the distance-specialised skiers. Therefore, the slower maximal velocities attained for the distance-specialised skiers were probably, in part, explained by an ineffective technical strategy and/or a physiological inability.

With DS (*Study II*) and HB (*Study III*) the absolute phase durations of the poling and kick decreased similarly as the velocity increased from moderate to high velocity. However, from high to maximal velocity during DS, the kick time decreased considerably less than the poling time (13% versus 29%), with no such pattern observed for HB. This difference is probably related to the considerably shorter kick duration at maximal velocity in DS than HB (0.14 versus 0.25 s), indicating that the critical time for leg force impulse application during DS was reached at the high velocity, due to the prolonged relative kick phase duration that was combined with a decreased cycle length at maximal velocity. In DS, the kick times observed across the different velocities are in agreement with earlier findings reported by Vähäsöyrinki et al. (2008), and the kick time at maximal velocity is comparable to the contact times reported for sprint running uphill (Weyand et al., 2000).

In the case of HB the relative phases (as percentages of a total cycle) of poling, leg thrust and recovery were constant across all the velocities, whereas for DS the relative kick was prolonged and the gliding phase shortened at maximal velocity. These findings emphasise the importance of fast and substantial leg-force generation, especially during DS, due to the limited time available for force application. This is especially important with respect to the leg thrust during classical skiing, since the ski must be stationary as force is applied to the ground, differing substantially from skating where the ski is gliding during the leg thrust (Smith, 2003).

5.2. KINETICS

The peak pole forces observed with DS and HB ranged from 15-25% and 13-25% of BW, respectively, values that are relatively high in comparison to DS roller skiing on a treadmill at velocities corresponding to the moderate intensity used in *Study II* (Björklund et al., 2010; Lindinger et al., 2009a). The observed gradual increase in peak pole forces with elevated velocities corroborate previous findings by Stöggl et al. (2011), showing a considerable increase (19% to 29% of BW) in peak pole force from submaximal to maximal DS roller skiing.

The peak leg forces were similar across all velocities for both sub-techniques (i.e., DS and HB), with peak forces of ~ 2 times BW, which is similar to previous findings for diagonal roller skiing (Lindinger et al., 2009a; Stöggl et al., 2011) and diagonal skiing on snow (Komi & Norman, 1987). In *Study III* the relative contributions of the resultant pole and leg forces to propulsion in HB were constant across velocities (~ 71% and 20%, respectively). In addition, of the total propulsive force generated, the poling and leg thrust contributed 23% and 77%, respectively. Thus, although pole forces are more effectively applied, leg forces contribute most to the total propulsion during HB.

The rate of force development for the leg thrust with both DS and HB increased with higher velocities, which is consistent with findings for running (Kram & Taylor, 1990), where faster velocities are primarily related to higher rates of force generation (Weyand et al., 2000). By contrast, Stöggl et al. (2011) observed no increase in the rate of force development for the leg thrust with an elevated DS roller skiing velocity. However, compared to the observations at a similar maximal velocity and incline by Stöggl et al. (2011), *Study II* revealed time to peak pole and leg forces that were considerably shorter (both ~ 25%) with higher rates of force development during poling (53%) and ski-loading (28%) for DS performed on snow. Hence, the importance of proper timing and the rate of leg force generation (here measured as the normal force generated on the insole of the ski boot) during roller skiing and skiing on snow might differ. When skiing on snow, considerable vertical forces must be applied rapidly during pre-loading and at the beginning of the kick phase in order to press down the grip waxed ski camber to attain sufficient static friction for the propulsive kick phase (Komi, 1987; Komi & Norman, 1987), which contrasts to roller skiing (Ainegren et al., 2013a). Accordingly, the ideal DS roller skiing and on-snow skiing techniques are likely to differ, a problem that has to be considered during the off-season when athletes are employing DS roller skiing for training, as well as a problem when generalising laboratory data to the field. In addition, the impact of leg force generation (perpendicular to the slope) increases with slope steepness, being highly important for steep uphill skiing with the HB sub-technique. Here, we observed that skiers load the inside forefoot extensively during the leg thrust, probably in order to create enough static friction to avoid slipping.

5.3. SPEED CAPACITY

The importance of V_{max} over a short distance (50 m) for sprint-skiing performance over a longer distance (1000 m) has been previously documented (Stöggl et al., 2006) and was also observed here (*Studies I*, *IV* and *V*). Since these previous findings are based on time trials, the importance of V_{max} is likely even greater during head-to-head races that usually finish with a short all-out spurt. The V_{max} is probably determined by a combination of factors, including muscular strength and anaerobic metabolic characteristics, as well as motor control (i.e., technical factors) (Rusko, 2003; Stöggl et al., 2006).

In *Study I*, G3-V_{max} was positively correlated to the relative use of G3 during the STT and the V_{peak} in the DP acceleration test was negatively related to STT time. In addition, skiers with a higher DP-V_{peak} utilised G3 to a greater extent during the STT and were faster over the steepest uphill section than slower skiers. This finding emphasises the necessity for high upper-body strength in sprint skiing, probably related to the substantial propulsive force generated by the upper body during uphill skating with G3 (Smith, 1992).

The importance of V_{max} was further confirmed in *Study IV*, where V_{max} in DP and DS were negatively correlated to the respective DP and DS total section times during the 1,300-m STT. In addition, *Study V* revealed that the best individual STT performances were characterised by more aggressive positive pacing strategies and skiers with the highest V_{max} utilised more aggressive pacing strategies. Therefore, short-interval speed training (20-s all-out intervals interspersed by 120-s of rest) designed to improve V_{max} may also improve performance over longer distances, as previously shown by Nilsson et al. (2004b). Altogether, these findings clearly illustrate the necessity of a high maximal speed capacity for success in modern c.c. sprint skiing.

5.4. AEROBIC ENERGY SUPPLY

In endurance sports the upper limit for aerobic metabolic rate (i.e., $\dot{V}O_{2max}$) is an important prerequisite for success (Joyner & Coyle, 2008; Saltin & Åstrand, 1967), and when comparing top athletes from different sports, male c.c. skiers have demonstrated remarkably high absolute (≥ 6 L/min) and relative (~ 80-90 mL/kg/min) $\dot{V}O_{2max}$ values (Burtscher et al., 2011; Holmberg et al., 2007; Ingjer, 1991; Rusko, 2003; Sandbakk & Holmberg, 2014; Strømme et al., 1977). Although world-class sprint skiers have similarly high absolute $\dot{V}O_{2max}$ values, relative values are somewhat lower (~ 70-80 mL/kg/min) than for the best distance c.c. skiers (Losnegard & Hallén, 2014; Sandbakk et al., 2010). At the same time, among a relatively homogenous group of athletes, other physiological and/or biomechanical factors may be equally crucial for success (Coyle, 1995; Joyner & Coyle, 2008).

In the current thesis, $\dot{V}O_{2max}$ on its own was not shown to be significantly related to the overall STT performance times observed in *Studies I* and *IV*, but was related to the ability to maintain uphill skiing velocity, with more even pacing strategies being employed by the skiers with the highest $\dot{V}O_{2max}$ values (*Study I*). Although rather speculative, the more even pacing strategies by the skiers' with the highest values of $\dot{V}O_{2max}$ may have been related to their potentially lower anaerobic capacity.

Even though an aerobic energy contribution of 82% was observed in *Study IV*, only 30% of the variation in STT performance could be related to the aerobic metabolic rate (i.e., performance $\dot{V}O_2$), with no significant correlation observed between $\dot{V}O_{2max}$ and STT performance. This corroborates previous findings by Stöggl et al. (2007) and Losnegard et al. (2012a) showing no clear relationships between $\dot{V}O_{2max}$ and sprint-skiing performance. By contrast, Sandbakk et al. (2011) observed a significant relationship between $\dot{V}O_{2max}$ and STT performance in an international competition.

These contrasting observations are likely related to different physiological characteristics of the participants involved in the different studies. Although some elite endurance athletes possess relatively low $\dot{V}O_{2max}$ values, they can still be successful. This is possible by compensating with a higher GE and/or fractional utilisation of $\dot{V}O_{2max}$, which indicate that "best-in-class" values for each performance factor are unlikely to appear in the same athlete (Joyner & Coyle, 2008; Lucia et al., 2002; Weston et al., 2000). Furthermore, c.c. skiing comprises several different sub-techniques and $\dot{V}O_{2max}$ in each sub-technique is important to performance. In *Study I* we observed that G3 was the most frequently used (~ 63%) sub-technique and hence the $\dot{V}O_{2max}$ in G3 is likely to be more important to performance than $\dot{V}O_{2max}$ in other sub-techniques.

In *Studies IV* and *V*, relatively low RER values were observed in DP at high sub-maximal intensities and the $\dot{V}O_{2max}$ attained using DP and DS were relatively similar. Moreover, the ratio of the respective $\dot{V}O_{2max}$ values in DP and DS was substantially higher compared to previous findings (0.96 versus 0.86) by Holmberg et al. (2007), and probably a consequence of an enhanced emphasis on specific upper-body endurance and strength training by elite skiers of today (Sandbakk & Holmberg, 2014).

5.5. GROSS EFFICIENCY (GE)

The most common concept of whole body efficiency is GE, defined as the amount of metabolic energy transferred to external work (van Ingen Schenau & Cavanagh, 1990). An alternative to GE is an expression of economy (Saunders et al., 2004) and several earlier studies on c.c. skiing have used this concept (Hoff et al., 1999; Hoffman, 1992; Hoffman & Clifford, 1990; 1992; Hoffman et al., 1994; Losnegard et al., 2013; Mahood et al., 2001; Mikkola et al., 2007; Millet et al., 1998a; Millet et al., 2003; Østerås et al., 2002). Movement economy is usually expressed as the $\dot{V}O_2$ at a given submaximal velocity or, alternatively, as the VO_2 per distance covered (mL/kg/m); i.e., the O_2 cost. However, since economy or O_2 cost do not take the different caloric equivalents for fat and carbohydrate into account, it is potentially more accurate to convert the O_2 cost to an energetic cost (J/kg/m) by combining the VO_2 and RER values (Weir, 1949). Since a lowering of the RER by 0.10 reduces the gross metabolic rate by 2.2% (Weir, 1949), it is perhaps surprising that $\dot{V}O_2$ or O_2 cost have been utilised to evaluate economy at various running intensities without considering the influence of substrate utilisation (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Helgerud et al., 2010).

Therefore, GE and energetic cost were analysed in *Studies IV* and *V*. The GEs associated with the DP and DS sub-techniques were, on average, ~ 16% and 20%, respectively, which are in agreement with previous observations using DP

(Lindinger & Holmberg, 2011) and DS (Ainegren et al., 2013b), but generally lower as compared to cycling at high work rates (Coyle et al., 1992; Gaesser & Brooks, 1975; Ettema & Lorås, 2009). Although a linear decline in GE with an elevated DP velocity was demonstrated by five skiers in *Study IV*, no significant relationship was observed between velocity and GE (*Study IV*). For DS, GE was independent of velocity (*Studies IV* and *V*). The GE for DS increased gradually with steeper inclines, whereas with DP the GE improved slightly up to an incline of 2.3° and fell at steeper gradients (*Study IV*). In addition, when expressed as an energetic cost, DP was more economical at inclines < 3.3° and DS at inclines > 3.3°, which is in agreement with Pellegrini et al. (2013).

The GE and economy values of elite cyclists and runners are typically better than those of amateurs (Lucia et al., 1998; Saunders et al., 2004). Among elite athletes with similar $\dot{V}O_{2max}$ values, factors such as GE and/or economy become increasingly important (Conley & Krahenbuhl, 1980; Costill et al., 1971; Weston et al., 2000; Lucia et al., 1998). In connection with world class cycling, Jeukendrup et al. (2000) calculated that a 1 percentage point increase in GE would lower the time required to cycle 40 km by 48 s. In addition, Sandbakk et al. (2011) showed a negative correlation between GE and sprint-race time (r = - 0.83) in a group of world-class skiers.

C.c. skiing can be considered as a technically complex endurance sport and as such, GE is likely strongly associated with performance. The relative importance of GE to sprint-skiing performance was assessed for the first time in *Study IV*, explaining 53% of the inter-individual variability in STT performance time, while $\dot{V}O_2$ explained only 30%. Even though the individual variations in $\dot{V}O_{2max}$ and GE were similar (CV = ~ 4.5%), GE was a better predictor of performance, perhaps at least in part because this measure is related to not only aerobic but also anaerobic metabolic demands. In addition, GE and O_2 cost have been observed to vary more than $\dot{V}O_{2max}$ during a training season in both cyclists (Hopker et al., 2009) and c.c. skiers (Losnegard et al., 2013). Therefore, the influence of training on GE should be tested on a regular basis and strategies designed to improve GE should be developed further.

5.6. ANAEROBIC ENERGY SUPPLY

In c.c. skiing sprint races are performed over undulating terrain at varying intensities, forcing skiers to alternate between different sub-techniques. Therefore, the production and distribution of anaerobic energy when alternating between the

DP and DS sub-techniques during self-paced STTs on a treadmill were analysed in *Studies IV* and *V*. At present, two commonly used approaches for estimating anaerobic energy production are the MAOD (Medbø et al., 1988) and GE (Serresse et al., 1988) methods. The MAOD method is regularly employed in sports where the external work, and hence the GE, cannot adequately be determined (e.g., in running), while the GE method is convenient for cycle ergometry where the external work is easy to quantify (Noordhof et al., 2013; van Ingen Schenau & Cavanagh, 1990). Although GE can also be determined during treadmill roller skiing (Sandbakk et al., 2010), previous examinations of anaerobic energy production during roller skiing at fixed uphill gradients have used the MAOD method exclusively (Losnegard et al., 2015; Losnegard & Hallén, 2014; Losnegard et al., 2012a; Losnegard et al., 2013; McGawley & Holmberg, 2014; Sandbakk et al., 2016). By contrast, GE was used for estimating the anaerobic energy production in the current thesis (*Studies IV* and *V*).

In *Study IV*, GE was influenced by both the skiing velocity and incline in a manner dependent on the sub-technique employed, so the conventional GE procedure for determining anaerobic energy production was inadequate. As such, a novel approach incorporating both velocity and incline had to be developed. This approach enabled estimation of the anaerobic energy supply during simulated sprint skiing over undulating terrain. Clearly, the potential influence of velocity and incline on GE should routinely be taken into consideration.

The anaerobic energy contribution of ~ 18% observed in *Studies IV* and *V* is consistent with previous values for other types of sporting events of similar duration (i.e., 210 to 250 s) (Bangsbo et al., 1993; Gastin, 2001; Spencer & Gastin, 2001). However, the absolute O_2 deficit of ~ 45 mL/kg was lower than previously reported for uphill (600-m, 7°) V1 and V2 ski-skating (Losnegard et al., 2012a) and DS skiing (McGawley & Holmberg, 2014). This difference may to some extent be related to the constant uphill gradients used in these previous studies and thereby providing no opportunity for the reconstitution of anaerobic energy during flat sections. Although the influence of incline on anaerobic capacity in c.c. skiing has not previously been evaluated, considerably greater (~ 60-80%) O_2 deficits have been observed in running when the slope gradient was elevated from 1% (0.6°) to 15% (8.5°) (Olesen, 1992; Sloniger et al., 1997), which also may be the case for c.c. skiing. This suggestion is supported by our finding that the peak O_2 deficit was reached after the second uphill section (Fig. 15C and 16D) and not at the finish line (*Studies IV* and *V*).

In *Study IV*, only 15% of the inter-individual variability in STT performance was related to variations in the total accumulated O_2 deficit. By contrast, Losnegard et al. (2012a) showed anaerobic energy production to explain ~ 50% of the inter-individual variability in sprint-skiing performance. These differences may be related to the ~ 35% longer STT completion times in the current thesis (*Studies IV* and *V*), with a lower relative anaerobic energy contribution (18% versus 26%), as well as differences in subject characteristics. Moreover, *Study V* showed that the intra-individual (i.e., within-athlete) variability in STT performance was highly (69%) related to variations in the O_2 deficit. This latter relationship confirms that the anaerobic component of metabolic power is more variable than the aerobic.

The relative anaerobic energy contribution in c.c. skiing is likely to vary between ~ 18-26% during sprint races (*Studies IV* and *V*; Losnegard et al., 2012; McGawley & Holmberg, 2014) and down to < 1% during long distance (i.e., 50 km) races (assuming a maximal O_2 deficit of ~ 50 ml/kg). However, intensity varies during c.c. ski races, with work intensities exceeding $\dot{V}O_{2max}$ during uphill sections (Norman et al., 1989; Sandbakk et al., 2011) and dropping below $\dot{V}O_{2max}$ during longer downhill sections (Rusko, 2003). Therefore, substantial production of anaerobic energy while skiing uphill is likely to attenuate the decline in $\dot{V}O_2$ on the subsequent downhill section, thereby enhancing the fractional utilisation of $\dot{V}O_{2max}$. Moreover, the irregular distribution of the anaerobic energy produced over the course (Figs. 15C, 16D) in the current thesis (*Studies IV* and *V*) provide some evidence for this assumption and sprint races on snow over an actual course that also include downhill stretches would probably result in an even more irregular distribution of anaerobic energy.

5.7. PACING STRATEGIES AND ASSOCIATED METABOLIC RESPONSES

During the 1425-m STT in *Study I*, a positive pacing strategy involving 3% more time spent on the second than the first lap was employed, while the positive pacing during all STTs in *Study V* involved 3-9% longer times on the second half (Fig. 17A). A beneficial aspect of positive pacing with a fast start may be related to faster $\dot{V}O_2$ kinetics (Aisbett et al., 2009; Bishop et al., 2002), as the time to reach $\dot{V}O_{2max}$ has been found to be inversely related to the starting intensity (Jones et al., 2008). In *Study V*, skiers reached their predetermined $\dot{V}O_{2max}$ in each respective STT after ~ 98 s, with no significant difference in the time to peak $\dot{V}O_2$ between STTs. This $\dot{V}O_2$ response supports earlier findings showing that elite athletes can reach near maximal $\dot{V}O_2$ values within 2-min of exhausting exercise (Hettinga et al., 2009).

The skiers with the highest V_{max} used more aggressive pacing strategies (*Study V*), while $\dot{V}O_{2max}$ was related to the ability to maintain uphill skiing velocity in *Study I*. These findings suggest that skiers adapt their pacing strategies not only to course length but also to their individual physiological and biomechanical abilities. The importance of a fast start was emphasised by the finding that the fastest trials involved an approximately 5% greater power output over the first half of the course (Fig. 16E), with a larger anaerobic energy supply but the same aerobic energy supply as in the slowest trial. Although an over-aggressive pacing strategy may be deleterious for overall performance due to premature fatigue, the worst performances in *Study V* were related to slower initial velocities where athletes were not able to make up for the lost time. Therefore, a too fast start and so called "over-pacing" does not seem to be a problem when well-trained skiers are performing self-paced 1300-m (~ 4 min) STTs on a treadmill. Conversely, Losnegard et al. (2012a) introduced a protocol that involved a relatively slow fixed starting velocity (10.8 km/h, ~ 100% of $\dot{V}O_{2max}$) during the initial 36 s (~ 21%) of the 600-m (~ 3 min) uphill (7°) skating time trial to avoid over pacing.

Unlike earlier laboratory studies of pacing performed on fixed inclines (Abbiss & Laursen, 2008), *Study V* involved a simulated course with both flat and uphill sections. As illustrated in Figure 16C and as hypothesised, more aggressive pacing was utilised on the uphill than on the flat sections, with considerably higher (~ 30%) metabolic rates for uphill DS than for flat skiing with DP. In addition, skiers with a greater body mass tended to take relatively longer to complete the uphill sections than lighter skiers. Altogether, this corroborates previous findings that elite skiers generate the highest metabolic rates during uphill skiing (Norman et al., 1989; Sandbakk et al., 2011) and shows that terrain-specific pacing is affected by the skiers body mass, which has been observed previously when modelling cycling performance (Boswell, 2012). The importance of uphill skiing for overall race results has been previously observed in traditional skiing by Berg & Forsberg (2008), who stated that more than half of the race time is spent uphill when the course contains equal amounts of uphill, downhill and flat terrain. This is comparable to sprint skiing on snow, where ~ 47% of the total STT time was spent during uphill skiing (*Study I*).

The benefits of more aggressive pacing on the uphill than on the flat sections may be related to a combination of physiological, biomechanical and mechanical factors. Skiers may generate larger maximal O_2 deficits during uphill compared to flat skiing, similarly to previous observations in running (Olesen, 1992; Sloniger et al., 1997). A linearly decreasing GE, or increasing energetic cost, was observed in four skiers during DP when the velocity was elevated (see Fig. 14B). No such effect could be observed during sub-maximal uphill DS skiing, which provides a rationale for the considerably higher power output and metabolic rate during uphill DS skiing. In addition, the higher power outputs and metabolic rates observed during uphill skiing may enhance skiing performance outdoors, primarily by reducing fluctuations in velocity and thereby overall air-drag (Sundström et al., 2013). Altogether, anaerobic capacity and power are probably key determinants of effective pacing, allowing athletes to work at considerably higher work rates uphill than on easier parts of the course that can be utilised for "anaerobic recovery" (i.e., decreasing the O_2 deficit).

5.8. TRANSITIONS BETWEEN SUB-TECHNIQUES

In c.c. skiing, Kvamme et al. (2005) proposed that O_2 cost is an important determinant of technique selection. They reported that G2 is more economical at gradients > 4.5°, while G3 is more economical < 4.5°. By contrast, no differences in O_2 cost or STT performance have recently been observed in elite skiers using these gears at 4-8° slope inclines (Losnegard et al., 2012a; b). Furthermore, during the 1,425-m STT in *Study I*, G3 was used at slope gradients up to ~ 9°, with higher-ranked skiers utilising relatively more G3 than G2. Therefore, gear selection was not determined solely by slope inclination, since skiing velocity and the length of the uphill slopes were also important factors.

The frequent alterations between sub-techniques unique to c.c. skiing are illustrated by the 21-34 gear transitions performed during the STT in *Study I*. Although it is commonly assumed that animals, including humans, change gait for lowering the energetic cost of movement (Hoyt & Taylor, 1981; Margaria, 1976), several studies (Minetti et al., 1994; Rotstein et al., 2005; Thorstensson & Roberthson, 1987) have proposed that the comfort of locomotion is a more important factor for a gait transition than a reduced energetic cost.

In *Study IV*, the spontaneous transition points between the DP and DS sub-techniques during a STT were analysed for the first time. Recent findings by Pellegrini et al. (2013) suggest that such transitions are related to a variety of factors, with force generation appearing to be one crucial determinant. However, a trade-off problem is likely to exist between different variables, such as force production, metabolic cost and muscular fatigue (Allen et al., 1995; Griffin et al., 2003; Hill, 1938; Minetti et al., 1994).

Study IV revealed that the preceding workload exerts a more pronounced influence on the spontaneous transition point than does the energetic cost, which is analogous to earlier findings for walk-to-run transitions (Hreljac, 1993; Minetti et al., 1994). Although the change from DP to DS involved no difference in metabolic cost, but with the reverse order of transition (DS to DP); skiers were changing to DP when DS still was less energy consuming. Thus, the early transitions to DP on steep inclines (4.5° and 4.8°) were probably related to comfort of movement, since the preceding DS was performed with considerably higher metabolic rates. Thus, potential fatigue in skiing muscles associated with DS resulted in an uneconomical (i.e. energetically too early) transition to DP at a relatively steep incline (~ 4.7°) in attempt to minimise exertion.

5.9. METHODOLOGICAL CONSIDERATIONS

In *Study III,* the propulsive force components were estimated as based on force balance (Frederick, 1992; de Koning & van Ingen Schenau, 2000), where gravity was considered as the only opposing force due to the steep uphill gradient (15°), slow skiing velocities (2.4-3.8 m/s) and absence of gliding. Even though the exclusion of air drag and potential force losses during the pole and leg thrusts have shortcomings, similar simplifications have been made during the analyses of running and walking on steep uphill terrain (Minetti et al., 2002).

Classical roller skiing with ratcheted wheels allows generation of static friction during the leg kick that is several times greater than that for skiing on snow, which allow skiers to generate high propulsive forces without the ski slipping and is thus less dependent on technical skills (Ainegren et al., 2013a). In *Study II*, the rates of leg/plantar force application were substantially higher for DS skiing on snow than for roller skiing at a similar velocity and incline (Stöggl et al., 2011), so that generalising results from the former to the latter may be questionable. Therefore, a more detailed analysis of such differences, including forces in both the normal and forward directions, is required (Kehler et al., 2014; Vähäsöyrinki et al., 2008).

A precise determination of GE and the aerobic and anaerobic energy contributions require accurate measures of $\dot{V}O_2$ (*Studies IV* and *V*). The $\dot{V}O_2$ was measured using a metabolic cart with a mixing chamber (*Studies I, IV* and *V*) (Jensen et al., 2002). This system was tested for validity against the "gold standard" Douglas bag system (Carter & Jeukendrup, 2002) during treadmill roller skiing at four different submaximal intensities (~ 50% to 85% of $\dot{V}O_{2max}$, RER ≤ 1.00), as described previously (Ainegren et al., 2013b). The typical error for the difference between the metabolic cart and the Douglas bag system was 0.07 L/min, indicating a high validity, with a smallest worthwhile difference (Mann et al., 2014) in $\dot{V}O_2$ of 0.20 L/min.

In *Studies IV* and *V* the O_2 deficit was estimated by using a modified GE method. The GE and MAOD methods are commonly applied for estimating the O_2 deficit during supramaximal exercise (Noordhof et al., 2013) and both methods have been shown to be similarly reliable (Noordhof et al., 2011). Although a low agreement between the estimated O_2 deficits with the GE and MAOD methods was reported by Noordhof et al. (2011), a high level of agreement has been demonstrated more recently (Andersson & McGawley, 2016). However, the main problem with both of these methods involves the assumption that the relationship between energy cost and power output or velocity is similar at supramaximal exercise, an error that has been proposed to amplify with higher supramaximal intensities (Bangsbo, 1998). The relatively long STT durations (~ 4 min) in *Studies IV* and *V* resulted in relatively low supramaximal intensities and should therefore have minimised this potential error. In addition, supramaximal 4000-m cycling time trials have recently been shown to decrease GE (from ~ 23% to 20.5%) (Noordhof et al., 2015), which might be a potential limitation with the GE method used for estimating the O_2 deficit. However, a previous study (Åsan Grasaas et al., 2014) showed only a slight decline in GE (15.5% to 15.2%) during high-intensity roller skiing, which indicates a relatively low potential effect of this parameter on the estimated O_2 deficit during c.c. skiing.

Although the O_2 deficit is often viewed as an exclusively anaerobic component, a small fraction of the measured O_2 deficit comes from oxidative phosphorylation from the O_2 stored in haemoglobin and myoglobin. However, these O_2 stores have been estimated to be ~ 6 mL/kg (Medbø et al., 1988; Milne, 1988) and constitute only a relatively small fraction (~ 10%) of the total O_2 deficit. To obtain a more accurate estimate of anaerobic capacity in c.c. skiers, other investigators (Losnegard et al., 2012a; McGawley & Holmberg, 2014) have subtracted the estimated stored O_2 (8.8 mL/kg) from the O_2 deficit. However, since the amount of stored O_2 can only be approximated (Medbø et al., 1988), no such adjustment was made here (*Studies IV* and *V*).

The skiers' V_{max} was analysed in all of the studies included in the current thesis. In *Studies I-III* all-out performances over short distances (~ 10-20 m) including a short run-up (30-40 m) were performed. These short all-out efforts were likely to provide measures of maximal anaerobic metabolic rate (Smith & Hill, 1991; Vandewalle et al., 1987). By contrast, the incremental V_{max} protocols for treadmill roller skiing in *Studies IV* and *V* were considerably longer (~ 60-90 s) and the associated V_{max} measure was probably more related to the total amount of anaerobic energy produced (i.e., anaerobic capacity) than maximal anaerobic metabolic rate (Vandewalle et al., 1987). Even though these two variables are usually related (Goslin & Graham, 1985; Maud & Shultz, 1986; Medbø & Burgers, 1990; Scott et al., 1991) they represent different metabolic entities (Minahan et al., 2007). However, Stöggl et al. (2006) showed that a short-distance (50 m, 7.6-9.8 s) DP V_{max} test conducted in the field was highly correlated ($r = 0.86$) to a longer duration (~ 68 s) incremental V_{max} test on a treadmill. In addition, both tests were highly reliable with a low individual test-retest variability (CV of 1.7-1.8%). Therefore, while short- and long-duration measures of V_{max} probably reflect slightly different physiological abilities, they appear to be closely related.

In *Studies I, IV* and *V* self-paced time trials were performed over a set distance (i.e., "closed-end" tests). Previous studies have shown time trials to be significantly more reliable than time-to-exhaustion tests that are "open end" (Jeukendrup et al., 1996; Schabort et al., 1998a; Schabort et al., 1998b). In *Study V*, the within-athlete variability in the STT performance times were low (1.3 ± 0.4%) and similar to previous findings (Hickey et al., 1992; Schabort et al., 1998b; Stone et al., 2011; Schabort et al., 1998a). In addition, the best performances in *Study V* were in the first and last trials, which were equally fast, indicating appropriate familiarisation and an ability to recover between trials. Although the reliability and/or validity may be questionable when conducting laboratory time trials for evaluating sports performance, a cycling ergometry time-trial performance was found to be highly correlated ($r = 0.98$) to an outdoor road race (Palmer et al., 1996). Altogether, self-paced laboratory time trials appear to be sufficiently reliable and race specific for monitoring sports performance.

6. CONCLUSIONS

In *Study I*, better performance in the 1425-m STT was closely related to faster uphill skiing and a greater utilisation of the G3 sub-technique. Additionally, the percentage of racing time using G3 was positively related to both G3-V_{max} and DP-V_{peak}. Moreover, $\dot{V}O_{2max}$ was related to the ability to maintain racing velocity on the uphill sections during the second lap. The skiers employed a positive pacing strategy, with a faster first than second lap. In addition, the decrease in velocity during the second lap was mainly related to slower uphill skiing, with a shift in gear choice from G3 towards a higher utilisation of G2.

In *Studies II* and *III*, increased skiing velocity from moderate to high (i.e., from ~ 63% to 80% of maximal velocity) with DS and HB were associated with synchronous increases of both cycle rate and cycle length, while further increases up to maximal velocity were solely related to a substantially higher cycle rate. At all velocities, leg thrust times were considerably shorter than poling times, especially in the case of DS, and the rate of force development during both the poling and leg thrust phases increased with higher velocities (*Studies II* and *III*). When DS velocity was elevated from high to maximal, the skiers shortened the relative gliding phase for a longer relative kick phase, thereby reducing the decline in absolute kick time. These observations emphasise the importance of a rapid generation of leg force in connection with DS (*Study II*). With HB, where gliding is absent, cycle rates were considerably higher (~ 22%) than with DS and absolute leg thrust times were considerably longer (~ 34%). In addition, 77% of the total forward propulsion was generated by the legs during HB (*Study III*). Altogether, these findings highlight the particular importance of leg-force generation during uphill classical skiing with the DS and HB sub-techniques (*Studies II* and *III*).

Studies IV and *V* revealed that the relative aerobic and anaerobic energy contributions during a 1,300-m STT (~ 4 min) were ~ 82% and 18%, respectively. Moreover, the novel GE method developed in this thesis enables the anaerobic energy supply during time trials involving multiple sub-techniques on varying inclines to be estimated. In the case of *Study IV*, multiple regression analysis revealed that $\dot{V}O_2$, O_2 deficit and GE explained 30%, 15% and 53%, respectively, of the total variance in STT performance time. In contrast to the low importance of anaerobic energy production for overall performance (*Study IV*), intra-individual (i.e., within-athlete) variations in performance during the four successive STTs were closely related (69%) to variations in anaerobic energy production (*Study V*). In *Study V*, positive pacing was employed throughout all the four STTs, with the best individual performances involving more aggressive pacing from the start. In addition, the pacing was regulated to the terrain, where considerably greater metabolic rates were generated on the uphill than on the flat sections of the course, resulting in an irregular distribution of the anaerobic energy reserve (*Studies IV* and *V*). Furthermore, the predetermined V_{max} was related to overall STT performance (*Study IV*), as well as to the pacing strategy, with skiers demonstrating higher V_{max} using more aggressive pacing.

7. PRACTICAL APPLICATIONS

The current thesis aimed to assess important biomechanical and physiological determinants of high velocity c.c. skiing, with a specific focus on sprint skiing. Findings showed V_{max} to be highly related to performance, suggesting that c.c. skiers should emphasise training of specific maximal strength, power and speed, as well as technical ability, to enhance sprint-skiing performance. These important aspects of maximal speed and motor control should be considered especially when designing training for children and youth (Bompa & Haff, 2009; Stöggl & Stöggl, 2013).

A fundamental biomechanical constraint during high-velocity skiing is the inverse relationship between force and velocity of the contracting muscles (i.e., a high shortening velocity results in a low force and vice versa). This is specifically problematic in classical skiing as the ski has to be stationary during the leg kick. In DS, kick times associated with V_{max} were similar to the contact times reported for uphill sprint running (~ 0.14 s) (Weyand et al., 2000). Therefore, training to enhance V_{max} should probably focus on a combination of maximal strength, power and speed training exercises, together with a particular focus on technique development. Such improvements may also enhance skiing economy as demonstrated previously (Hoff et al., 1999; Mikkola et al., 2007; Østerås et al., 2002; Helgerud et al., 2001).

The current thesis also provides support for the high importance of GE (or energetic cost/economy) for c.c. skiing performance, which emphasises the need for regular testing of GE in addition to other common physiological tests (i.e., $\dot{V}O_{2max}$ and lactate thresholds). Moreover, a decline in GE with an elevated DP velocity was evident in some skiers during the high-intensity submaximal test. Although specific mechanisms that explain such a decline in GE need further investigation, it may, at least in part, be related to the aforementioned force-velocity constraint associated with high muscle contraction velocities with an increased energetic cost of generating force (Barclay et al., 1993; Houdijk et al., 2006; Kram & Taylor, 1990).

The performance of elite sprint c.c. skiers during a one-year season was monitored by Losnegard et al. (2013), who found a considerable improvement (7%) from June to January in 1000-m uphill skating time-trial performance. This improvement was only associated with an enhanced anaerobic capacity and economy, whereas the $\dot{V}O_{2max}$ remained unchanged (~ 79 mL/kg/min). Therefore, when athletes have reached their upper ceiling for $\dot{V}O_{2max}$, other decisive performance factors (such as fractional utilisation of $\dot{V}O_{2max}$ and GE) need to be emphasised during testing and training. Moreover, since c.c. ski races are performed on undulating terrain at intermittent intensities, the magnitude and distribution of anaerobic energy contributions may be highly important, most likely also influencing $\dot{V}O_{2max}$ utilisation during a race, since the aerobic and anaerobic energy systems are interrelated (Skiba et al., 2012; Jones et al., 2008).

In the current thesis, individually self-paced sprint-skiing time trials were performed with positive and variable pacing and were usually finished with a short all-out end spurt. Although a fast starting strategy is generally associated with a fast $\dot{V}O_2$ response that potentially can enhance performance (Jones et al., 2008), over-aggressive pacing with a large initial depletion of the anaerobic energy reserve can induce early fatigue that leads to a deterioration in performance (de Koning et al., 2011; Tucker & Noakes, 2009). Skiers' should also consider the mechanical advantage of increasing work intensity during uphill terrain for reducing the overall velocity fluctuations and hence the total air-drag (Sundström et al., 2013). Furthermore, in sprint skiing the knock-out heats after the individual qualification impose an additional determinant of pacing, i.e., the regulation of the work intensity with regard to the opponents' pacing decisions and race tactics (Konings et al., 2015; Konings et al., 2016; Tomazini et al., 2015). Therefore, different pacing strategies should be evaluated during race-simulated training, performed individually and head-to-head, over various ski-courses in order to adapt the regulatory mechanisms of pacing and race tactics toward an optimum, which may allow a maximised utilisation of the energetic resources with regard to the finishing point (de Koning et al., 2011; St Clair Gibson et al., 2006; St Clair Gibson & Noakes, 2004; Ulmer, 1996).

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