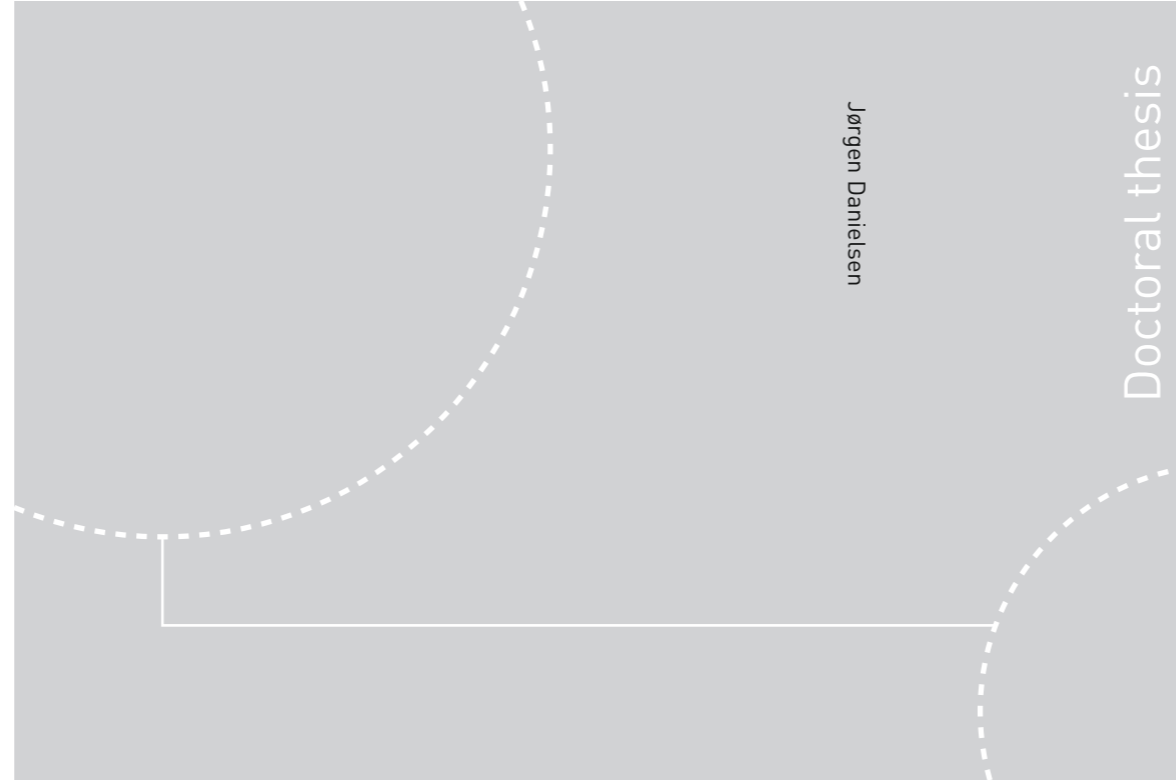


ISBN 978-82-326-3518-4 (printed ver.)
ISBN 978-82-326-3519-1 (electronic ver.)
ISSN 1503-8181



Jørgen Danielsen

Doctoral thesis

Doctoral theses at NTNU, 2018:365

Jørgen Danielsen

Energetics and dynamics of double poling cross-country skiing



Norwegian University of
Science and Technology



NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
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Science

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Thesis for the Degree of Philosophiae Doctor

Trondheim, November 2018

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Doctoral theses at NTNU, 2018:365

Printed by NTNU Grafisk senter

Table of contents

List of publications	iii
Summary	iv
Sammendrag	vi
Acknowledgements	ix
Introduction	1
Propulsion.....	1
Cross-country skiing (XC-skiing)	1
Propulsion mechanics in classical style XC-skiing	3
Importance of double poling in XC-skiing.....	4
Traditional double poling	5
Modern double poling	6
Mechanics of double poling	7
Purposes	11
Methods	12
Participants	12
Protocols.....	12
Measurements, instruments and materials.....	13
Analysis	14
Statistics	18
Results	19
Study I	19
Study II.....	23
Study III.....	26
Discussion	31
Effect of intensity, speed and incline-speed combinations.....	31
How does lower-extremity power contribute to propulsion power?	33
Stretch-shortening and power transfer mechanisms	38
Methodological considerations.....	40
Future lines of investigation	41
Conclusions	43
References	45
Paper I-III	

List of publications

This thesis is based on the three studies listed below which are referred to by their Roman numerals throughout the text.

- I** Danielsen J, Sandbakk Ø, McGhie D, Ettema G (2018) The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers. *Hum Mov Sci* 57: 83-93

- II** Danielsen J, Sandbakk Ø, McGhie D, Ettema G (2018) Mechanical energy and propulsion mechanics in double-poling roller skiing at increasing speeds. Pending submission to *Sports Biomech*

- III** Danielsen J, Sandbakk Ø, McGhie D, Ettema G (2018) Energetics and dynamics of double-poling roller-skiing at different incline-speed combinations at equal work rates. Submitted to *PLoS One*

Summary

Cross-country skiing is a complex endurance sport where the skier can choose between several sub-techniques over the course of a race. Essentially, the sub-techniques differ with regard to how propulsive forces are applied to the ground through the skis and/or the poles, where choice of sub-technique depends mostly on incline and speed. Double poling (DP) is the only sub-technique where the propulsive force is applied solely through the poles while the skis continuously glide forward parallel to the track. The upper-extremity muscles have therefore been considered the prime movers in DP. However, previous studies have shown that also the lower extremity plays an important role for optimal technique in high-performance DP, in part by generating mechanical energy through heightening of the body during the swing phase which subsequently can drive propulsion during the poling phase. Nevertheless, there is a lack of information concerning the specific sources of generation and destination of mechanical energy in DP (e.g., upper vs. lower extremity). Therefore, the main aim of this thesis was to examine the energetics and dynamics of DP in different conditions. One main question was how, and how much, lower-extremity power generation contributes to propulsion power through the poles in various DP conditions.

A total of 21 male Norwegian elite skiers, of both national and international level, volunteered to participate. Study **I** examined the effect of intensity in ergometer DP, study **II** examined the effect of speed in roller-skiing DP on the level and study **III** examined the effect of incline-speed combinations in uphill roller-skiing DP. Motion capture analysis was used to derive body mechanical energy fluctuations and the rate of change. From kinematics and dynamics, linked segment modelling was used to compute joint moment and power, as well as upper-extremity (shoulder+elbow) and lower-extremity and trunk (trunk+hip+knee+ankle) power. The relative power contribution from the upper extremity and lower extremity and trunk towards total power output (external work rate; WR) was calculated.

In ergometer DP (study **I**), the upper extremity contributed 51% of the total power output (i.e., pole propulsion power) during low-intensity DP (WR 116 W) and decreased ($P<0.05$) to 33% during maximal-intensity DP (3 min performance test; WR 306 W). In roller-skiing on the level (study **II**), this contribution amounted to 63% during low-speed DP (15 km·h⁻¹; WR 98 W) and increased ($P<0.05$) to 66% during high-speed DP (27 km·h⁻¹; WR 176 W). In uphill DP (study **III**) on slight and steep inclines (5% and 12% incline, respectively), speed was set to give equal WR at both inclines. No effect of WR (142 W – 238 W) was found on upper-extremity contribution in either slight (9.3 – 15.5 km·h⁻¹) or steep (4.8 – 7.9 km·h⁻¹)

uphill DP ($P>0.05$). However, upper-extremity contribution was 63% on slight incline, which was higher than the 54% contribution on steep incline ($P<0.05$). Based on these values, it can be concluded that the lower extremity contributes significantly to the total power output which is fully delivered externally through the poles. How this is made possible was similar between all conditions. Lower-extremity power generation occurs partly during the end of the poling phase, but mostly during the swing phase. The work done by the lower extremity during body heightening increases body mechanical (mainly potential) energy. As such, lower-extremity work is temporarily ‘stored’ as body mechanical energy. During the following poling phase, the body is leaned forward and rapidly lowered and part of the body mechanical energy (potential and kinetic energy perpendicular to the surface) is transferred to pole (or rope) propulsion power as the body exerts force on the poles (or ropes). During the poling phase, the upper extremity (mainly shoulder) generates considerable power that instantaneously drives pole propulsion power.

Some of the body mechanical energy generated during the swing phase is absorbed by the lower extremity during the following poling phase (that is, the part of the decreasing body energy not directly used for propulsion through the poles). This aspect was especially apparent in roller-skiing DP on the level (study **II**). Although this may seem energetically ineffective, some of this absorbed energy may be stored elastically and reutilised during the bouncing-like transition from body lowering to heightening. In uphill DP (study **III**), the amount of absorption by the lower extremity decreased at slight incline and was further reduced at steep incline. Increasing slope creates different boundary conditions, e.g., with the force of gravity acting at an angle to goal-directed movement (i.e., surface), not perpendicular as on the level. To maintain dynamic force balance, the skier adjusts body and pole positioning accordingly. In study **III**, a hypothesis related to incline was that the lower extremity could contribute less at steep incline because of this incline effect on the gravity-surface relation. This was not confirmed at the inclines and intensities studied here. The lower speed and gravity-surface relation on steeper incline leads to (much) longer poling times and shorter swing times. Altogether, on steep incline DP it seems as if body and pole positioning related to the boundary conditions become less advantageous for effective upper-extremity power generation. At the same time, more upper-extremity power was generated on slight incline at a lower perceived effort than at steep incline. From this it can be hypothesised that the upper-extremity muscles operate within a less advantageous range of the force-length-velocity relationship, which likely is a part of the interplay between several factors that make skiers not prefer DP on steep incline.

Sammendrag

Langrenn er en kompleks utholdenhetsidrett hvor utøveren kan velge mellom flere ulike delteknikker underveis i en konkurranse. Den essensielle forskjellen mellom delteknikkene er hvordan framdriftskraft skapes via skiene og/eller stavene, hvor valg av delteknikk for det meste avhenger av stigning og hastighet. Staking er den eneste delteknikken hvor framdriftskraft utelukkende kommer via stavene, mens skiene kontinuerlig glir framover parallelt med sporet. På grunn av dette har musklene i overekstremiteten blitt ansett som de primære bidragsyterne til framdrift i staking. Flere studier har imidlertid vist at underekstremiteten spiller en sentral rolle for optimal teknikk i staking på høyt nivå, blant annet ved å generere mekanisk energi i svingfasen som senere kan brukes til framdrift i stakfasen. Det er likevel mangel på forståelse vedrørende hvor mye mekanisk energi som skapes i de ulike delene av kroppen (f.eks. overekstremiteten versus underekstremiteten) i staking. Det overordnede målet med denne avhandlingen var å studere energetikk og dynamikk i staking i ulike kondisjoner. Et av hovedspørsmålene som ble undersøkt var hvordan, og hvor mye, underekstremiteten bidrar til framdriftskraft og effekt gjennom stavene i ulike stak kondisjoner.

Totalt deltok 21 norske eliteskiløpere på både nasjonalt og internasjonalt nivå. Studie **I** undersøkte effekten av intensitet i ergometerstaking, studie **II** undersøkte effekten av hastighet ved staking på flatmark på rulleski og studie **III** undersøkte effekten av ulike stigning-hastighet-kombinasjoner i motbakkestaking på rulleski. Videobasert bevegelsesanalyse ble brukt for å utlede kroppens energifluktueringer samt energiendringsrater. Fra kinematikk og dynamikk ble segmentmodellering brukt for å kalkulere moment og effekt i ledd, herunder effekt i overekstremiteten (skulder+albue) og i underekstremiteten og trunkus (trunkus+hofte+kne+ankel). Det relative effektbidraget fra over- og underekstremiteten til total ytre effekt (arbeidsrate; WR) ble så kalkulert.

I staking på ergometer (studie **I**) var bidraget fra overekstremiteten 51% av total effekt ved lav intensitet (WR 116 W) og ble redusert ($P<0.05$) til 33% ved maksimal intensitet (3-min prestasjonstest; WR 306 W). På rulleski på flatmark (studie **II**) var dette bidraget 63% på lav hastighet ($15 \text{ km}\cdot\text{t}^{-1}$; WR 98 W) og økte ($P<0.05$) til 66% på høy hastighet ($27 \text{ km}\cdot\text{t}^{-1}$; WR 176 W). I motbakkestaking (studie **III**) på moderat og bratt stigning (5% og 12% helling) ble hastigheten justert for å matche WR på begge stigningene. Ingen effekt av WR (142 – 238 W) ble funnet for bidraget fra overekstremiteten ved hverken moderat ($9.3 - 15.5 \text{ km}\cdot\text{t}^{-1}$) eller bratt ($4.8 - 7.9 \text{ km}\cdot\text{t}^{-1}$) stigning ($P>0.05$). Derimot var bidraget fra overekstremiteten ved moderat stigning høyere enn ved bratt stigning (63% vs. 54%, $P<0.05$). Basert på disse verdiene kan det

konkluderes med at bidraget fra underekstremiteten til total effekt, som fullt ut leveres eksternt via stavene, er betydelig. Måten dette blir muliggjort på var grovt sett lik mellom de ulike kondisjonene. Underekstremiteten generer noe effekt på slutten av stakfasen, men hovedsakelig i svingfasen. Arbeidet gjort av underekstremiteten gjennom å heve kroppens tyngdepunkt øker kroppens mekaniske (hovedsakelig potensielle) energi. På denne måten blir arbeid gjort av underekstremiteten midlertidig 'lagret' som mekanisk kroppsenergi. Under den påfølgende stakfasen blir kroppen lent framover og raskt senket slik at en del av kroppsenergien (potensiell og kinetisk energi vinkelrett på overflaten) blir overført til framdriftseffekt i stavene (eller tauet). Under stakfasen genererer overekstremiteten (hovedsakelig skulder) betydelig effekt som umiddelbart fører til framdriftseffekt i stavene.

En del av kroppsenergien generert av underekstremiteten i svingfasen blir absorbert av underekstremiteten i den påfølgende stakfasen (dvs. den delen av den minkende kroppsenergien som ikke blir direkte brukt til framdriftseffekt gjennom stavene). Dette aspektet var spesielt tydelig ved staking på flatmark (studie **II**). Selv om dette kan virke energetisk ineffektivt kan noe av den absorberte energien bli lagret elastisk og gjenbrukt under den sprettlignende overgangen fra kroppssenkning til kroppsheving. Ved staking i motbakke (studie **III**) var mengden absorpsjon i underekstremiteten redusert ved moderat stigning og ytterligere minsket ved bratt stigning. Økende helling gir ulike grensebetingelser, f.eks. så virker ikke gravitasjonskraften vinkelrett til målrettet bevegelse (underlag), slik den gjør på flatt underlag. For å beholde dynamisk kraftbalanse justerer skiløperen posisjoneringen av kropp og staver deretter. I studie **III** var en hypotese relatert til økt stigning at underekstremiteten ikke kan bidra like mye på bratt som moderat stigning på grunn av effekten helling har på forholdet mellom gravitasjon og underlaget. Dette ble ikke bekreftet på stigningene og intensitetene studert i denne studien. Den lavere hastigheten og vinkelen mellom gravitasjon og underlag på bratt stigning fører til (mye) lenger stakfase og kortere svingfase. Det ser ut til at kropps- og stavposisjoneringen ved staking på bratt stigning, som er relatert til de ulike grensebetingelsene, er mindre fordelaktig for effektiv generering av effekt i overekstremiteten. Samtidig ble det generert mer effekt i overekstremiteten på moderat stigning, selv om det ble oppfattet mindre anstrengende enn ved bratt stigning. Ut fra dette kan en hypotese være at musklene i overekstremiteten opererer under mindre fordelaktige kraft-lengde-hastighetsforhold, som antakeligvis er en del av samspillet mellom de ulike faktorene som fører til at skiløpere foretrekker diagonalgang framfor staking i bratt motbakke.

Acknowledgements

I would like to thank the Department of Neuromedicine and Movement Science, NTNU, where the work for this thesis was carried out, for the opportunity and support along the way.

I sincerely need to thank:

My supervisor, Gertjan Ettema, for sparking my interest in research during your lectures on biomechanics in 2009, for guiding me through the world of science, for your rock solid opinions about what science is and should be, for challenging and trusting me, and for always taking the time to answer and discuss any questions.

My co-supervisor, Øyvind Sandbakk, for bringing me into the field of cross-country skiing research, for often forcing me to zoom out and see the bigger picture, and for sharing your vast knowledge about cross-country skiing and performance.

All the people at SenTIF and Olympiatoppen Midt-Norge, for creating a positive environment, making it a pleasure going to work every day. The amount of knowledge in this building is immense. Thanks to Conor Bolger for the daily existential office discussions, and later to Julia Baumgart for the same.

All the skiers that took part in the studies, for being interested in knowing what we do with all the stuff that all of a sudden is attached to your bodies.

My friends and family, especially mamma and pappa, for raising me, for your support and love and for your interest. My sister Marit and my brother Jonas, for endless talks about everything and nothing, for the love and support, and for all the care and fun we share.

Ann, for being you.

Introduction

Propulsion

In human locomotion, propulsion can be defined as acceleration of the body centre of mass (CoM) relative to the environment. For propulsion to occur, a source of mechanical energy or power is needed along with a propulsor, i.e., a device that converts this energy into external power via a propulsive force. For humans and animals, muscles are the power source, and the limbs (legs and/or arms) are usually the propulsors. In all locomotor activities, propulsion is only possible by generation of propulsive forces against the environment. In most such activities, e.g., walking and running, the propulsive push-off takes place against a fixed point on earth in the direction opposite to the desired movement direction. As a consequence of the backward push-off against the ground, the reaction force propels (accelerates) the CoM forward.

Cross-country skiing (XC-skiing)

In cross-country skiing (XC-skiing), skis and poles are used as a way of transport across terrain that is covered with snow and these tools, especially the poles, can be viewed as additional propulsors. XC-skiing is therefore often described as a quadrupedal gait. XC-skiing locomotion dates back more than 4000 years (Clifford, 1992) and has since then evolved enormously, especially by advancement of the equipment used. Today's skis and poles are made of carbon fibre and composite materials, and fluorocarbon waxing is used to minimize ski-snow friction. This has led to a decrease in the energetic cost of transport. It has been estimated that the XC-skiing speed today is twice as high at a given metabolic rate as it was 1500 years ago (Formenti, Ardigo, & Minetti, 2005). In the sport setting, competitive XC-skiing has been on the Olympic program since the first Winter Olympics in Chamonix, France, in 1924, while the first known XC-skiing competition was held in Tromsø, Norway, in 1843 (Clifford, 1992; Sandbakk, 2017).

Today, competitive XC-skiing consists of two styles, the classical style and the skating style. Both styles normally are performed on the same racecourses in World Cup and Olympic racing. The length of a racecourse vary considerably, from ~1.5 km sprint competitions to 50 km distance races (Sandbakk, 2017; Sandbakk & Holmberg, 2014). Total race time may vary from ~3 min during sprint races (to win, these must be repeated 4 times: a time trial prologue followed by three knock-out heats) to ~2 hr during 50 km races. In addition, long-distance XC-skiing (Ski Classics, including the 90 km Vasaloppet, the 70 km Marcialonga) has become increasingly popular among both professional elite and amateur skiers. The winning time in

these races often approach 4 ½ hrs. A typical Olympic or World Cup racecourse is regulated by the International Ski Federation to consist of approximately 1/3rd uphill terrain (incline between 9-18%, including some short sections steeper than 18%), 1/3rd undulating terrain (including level terrain, and very short climbs and downhill) and 1/3rd downhill terrain. Because of the varying terrain in XC-skiing, both styles consist of several sub-techniques which may be considered as a gearing system (Table 1). Basically, the sub-techniques differ in the way propulsive forces are applied through the poles and/or the skis, and thereby the amount of involvement of the upper – and lower body is strongly dependent on the sub-technique used. Though many factors influence the choice of sub-technique (e.g., Dahl et al., 2017; Pellegrini et al., 2013), incline and speed are the two major determinants.

Table 1. Overview of most important sub-techniques used in XC-skiing.

Classical	Skating	Incline	Speed
Herringbone	G1	Uphill	Low
Double poling with kick	G2	↓	↓
Diagonal stride	G3		
Double poling	G4		
Static tuck	Static tuck	Downhill	High

High-performance XC-skiing demands a high rate of metabolic energy liberation and a high gross efficiency, i.e., the (technical) ability to convert metabolic rate into external power and speed (e.g., Sandbakk & Holmberg, 2014; Sandbakk et al., 2010). When XC-skiing at a given steady-state incline and speed, the mean external power output is in balance with the rate of work done against external resisting forces:

$$\dot{E} e_{\text{gross}} = P_{\text{mean}} \text{ and } P_{\text{mean}} = P_{\text{air}} + P_{\text{g}} + P_{\text{fr}} \quad [1]$$

where \dot{E} is metabolic rate, e_{gross} is gross efficiency, P_{mean} is the mean external power output (or work rate) and P_{air} , P_{g} and P_{fr} is the power lost to air resistance, gravity and snow friction, respectively (e.g., van Ingen Schenau & Cavanagh, 1990). The degree to which power is lost to these sources varies considerably with incline and speed, but gravity and friction usually dominates. At a given incline and speed, P_{mean} is about similar and independent of the sub-

technique used. However, within one movement cycle, the instantaneous external power output (P_o) may fluctuate considerably and differently depending on sub-technique. This is most essentially due to differences in the way propulsive forces are generated in each sub-technique, which in turn relates to differences in e_{gross} between sub-techniques (e.g., Andersson et al., 2017; Dahl et al., 2017).

Propulsion mechanics in classical style XC-skiing

In the classical style XC-skiing the two dominating techniques are diagonal stride (DIA) and double poling (DP). DIA is mainly used at steeper inclines while DP usually is used on flatter parts of a course. In DIA, propulsive forces are applied through both the poles and skis. The kinematics of DIA resembles walking or running with the arms and legs moving in an anti-symmetrical synchronous fashion. The propulsion period of the left pole is accompanied with propulsion from the right ski and vice versa. Moreover, the propulsion period from the left and right poles mostly overlaps, leading to an almost continuous pole propulsion time throughout one movement cycle (Dahl et al., 2017; Pellegrini et al., 2014). The skis allow for a gliding phase on each ski following the ski propulsion period, thus allowing for considerable longer cycle lengths than in walking or running. For ski propulsion to occur in DIA, the skis must be stationary in contact with the ground and grip waxing is required for sufficient grip between the ski and snow. At higher speeds the ability to effectively perform a ski push-off against a fixed point on the ground becomes difficult (Pellegrini et al., 2013). This is because during the ski propulsion period the maximal horizontal velocity difference that can be achieved between the stationary ski and the body CoM is approached (e.g., van Ingen Schenau et al., 1987). Thus, at higher speeds it becomes essentially impossible to effectively generate propulsive ski forces in DIA, which means that maintaining or increasing a high P_{mean} and thus speed becomes very challenging.

In DP the skis continuously glide forward. It is essentially impossible for a forward-gliding system to exert force on the underlying surface in direction opposite to the gliding direction. Thus, in DP propulsive forces are provided solely through the poles, by symmetrical and synchronous poling actions of both poles simultaneously. The principle for ski propulsion in DIA also applies to the poles, both in DIA and DP. That is, the poles are fixed to the ground during propulsion. However, the link from the stationary pole tips in contact with the ground to CoM has a longer range of motion than the link from skis to CoM. This allows for a higher mean skiing speed when relying on poling only as in DP, i.e., the time limiting effective pole propulsion occurs at a higher speed. Moreover, in pole propulsion, the skier has more

possibilities than in ski propulsion that allows for a longer pole propulsion time at a given speed, both in DIA and in DP. For instance, the skier can adjust the placement of the poles onto the ground quite far in front of the CoM, increasing pole propulsion time. Therefore, when mean skiing speed becomes high enough (usually on flatter sections) DP is preferred simply for mechanical reasons. Since both poles simultaneously generate propulsion, total propulsion time in DP is lower than in DIA (Dahl et al., 2017), and may be as low as 0.2 s or ~20-25% of total cycle time.

Altogether, these two sub-techniques differ considerably in the way propulsive forces are applied, which in turn is related to differences in e_{gross} . For example, both Andersson et al. (2017) and Dahl et al. (2017) found that e_{gross} is higher for DP than DIA at flatter sections and that this relationship is reversed at steeper inclines (at the same P_{mean}).

Importance of double poling in XC-skiing

During the last two or three decades, the usage of DP in classical style XC-skiing has increased. Saltin (1997) described that while DP became increasingly used during the 1990's, there was a simultaneously increase in the fraction of maximal oxygen uptake that skiers were able to reach while DP or arm cranking (relying exclusively on upper-extremity power). This development has continued during the last two decades. Traditionally, DP was used mainly on the flatter parts of a course. Nowadays, however, skiers often choose DP exclusively, also in races that contain steep uphill sections (Welde et al., 2017) in which diagonal stride (DIA) is the preferred technique (Dahl et al., 2017; Pellegrini et al., 2013). If a skier choose to DP exclusively throughout a race, the skis only need to be waxed for optimal gliding as in skating XC-skiing. Thus, though DP may be slower than DIA on steep uphill sections, more energetically costly and induce greater sense of effort (Dahl et al., 2017), skiers typically view this as a beneficial investment due to greater speed abilities on the flatter and downhill sections. These issues must be thoroughly considered before each race though, with especially snow conditions playing a large role. Certain snow conditions require certain grip waxing for DIA that induce greater gliding friction on the flat and downhill sections, and typically favours DP more.

The increasing utilization of DP has many reasons. Factors contributing to this development are better track preparation and further improved equipment (skis and poles), the introduction of new XC-skiing race formats (like the sprint discipline in the late 1990s), and the fact that a large fraction of XC-skiing races in later years involve mass starts where the outcome of the race often is decided during a final spurt on flat terrain where high speed is required. As a consequence of these changes in competitive XC-skiing, skiers have

simultaneously altered their training and a larger emphasis is now on upper body endurance -, strength - and power training as well as on the ability to generate high speed (Sandbakk, 2017; Sandbakk & Holmberg, 2014). Concurrently, the technical execution most XC-skiing sub-techniques have evolved, especially concerning DP.

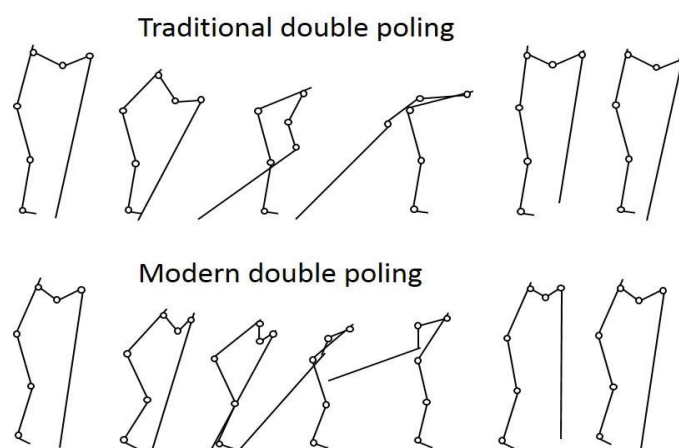


Figure 1 Stick-diagrams illustrating the most essential characteristics of traditional and modern double poling.

Traditional double poling

The fact that the poles provide all the propulsive forces is perhaps one of the reasons for why DP traditionally was considered to consist of solely upper-body work, while the functionality of the legs was restricted to provide an upright position and balance (Gaskill et al., 1999; Hoff et al., 1999; Mittelstadt et al., 1995). However, this reasoning is probably also due to the way in which the DP technique traditionally was executed. Figure 1 shows a typical example of one movement cycle of traditional high-speed DP, which was characterized by little range of motion of the lower extremities and large amplitudes of trunk flexion and extension. Moreover, the arms were quite extended at pole plant and with small flexion-extension movements in the elbows during the poling phase (i.e., propulsion phase, part of the cycle in which the poles are in contact with the ground). In traditional DP the ability to increase speed was found to be limited. Whereas speed increases in most other XC-skiing sub-techniques were achieved by both an increase in cycle rate (CR) and cycle length (CL), increasing DP speed was restricted

to an increase in CR only (Hoffmann et al., 1995; Millet et al., 1998; Nilsson et al., 2004). This was explained by the constraints of DP in that propulsive forces are applied solely through the poles. Because of the lower muscle mass in the arms (assumed to be the prime movers), the ability to generate large pole forces was limited.

Modern double poling

Figure 1 also shows the essential characteristics of the more modern high-speed DP (Holmberg et al., 2005). Today, high-performance DP (Holmberg et al., 2005; Lindinger et al., 2009; Stöggl & Holmberg, 2011, 2016) involves pronounced range of motion of the lower extremities and lower amplitudes of trunk flexion and extension. The shoulders are more abducted and the elbows more flexed at pole plant with a greater forward lean of the body immediately preceding pole plant. During poling, larger flexion-extension movements of the elbow are evident and elbow flexion during the first part of poling is synchronized with rapid flexion of the trunk, hip, knee and ankle joints. In essence, there is an emphasis on greater engagement of the lower extremity and trunk throughout the cycle, thereby more actively using body mass to generate large pole forces. Today, increasing speed in DP is achieved by increases of CL as well as CR (Lindinger et al., 2009). As such, elite skiers can achieve DP speeds >30 km/h (Stöggl & Muller, 2009). Altogether, DP nowadays is characterized by dynamic whole-body movements where the legs are essential in generation of propulsive force in an altogether 'explosive' and dynamic manner (Hegge et al., 2016; Holmberg et al., 2006; 2005; Lindinger et al., 2009; van Hall et al., 2003). If the range of motion of the lower-extremities is forcefully restricted, both efficiency and performance decreases (Hegge et al., 2016; Holmberg et al., 2006).

When increasing DP intensity or speed, the abovementioned characteristics become increasingly apparent. Whereas low-intensity DP (slow speed) typically bears resemblance to the traditional technique (mainly arm work), when intensity or speed is to be increased one relies progressively more on the lower extremity (Bojsen-Møller et al., 2010; Lindinger & Holmberg, 2011; Lindinger, Stöggl, et al., 2009; Rud et al., 2014; Zoppirolli et al., 2017). For example, Rud et al. (2014) found that an increase in P_{mean} during ergometer DP was mainly due to increased lower-extremity involvement. Whereas arm oxygen uptake increased by 20%, leg oxygen uptake increased by 53%. Using positron emission tomography, Bojsen-Møller et al. (2010) found an increased glucose uptake of the lower body but not the upper body muscles when DP intensity was increased. Zoppirolli et al. (2017) found that mean electromyography activity increased in the lower-extremity muscles with no increase in upper-extremity muscles when on-snow skiing speed was increased.

The increased lower-extremity involvement at higher DP speeds or intensities seem to be coupled to the increased vertical fluctuation of the body CoM. That is, the repetitive heightening and lowering of the body throughout the DP cycle increases with speed or intensity (Lindinger, Stöggl, et al., 2009). Explanations for this increased lower-extremity involvement have mainly been concerned with enhancing the ability to use body mass to increase pole forces. At higher speeds, the available time for pole propulsion necessarily decreases. Therefore, to maintain or even further increase P_{mean} and speed, pole forces must be rapidly increasing with peak pole force reaching >400 N (Stöggl & Holmberg, 2016), leading to peak pole propulsion power ~ 1500 W, though P_{mean} may be 300-400 W (Danielsen et al., 2015). The only way to achieve such high pole forces and peak powers seem to be to effectively use body mass which relies on the trunk and lower extremities (e.g., Holmberg et al., 2006). At submaximal intensities, it also seem beneficial to rely on a better developed whole-body movement pattern (Holmberg et al., 2006; Holmberg et al., 2005; Lindinger & Holmberg, 2011), thereby generating larger forces in a shorter time. This allows a larger fraction of the total work done to be distributed to the large muscle mass located in the trunk and lower-extremities. Moreover, the longer swing times thus achieved provides longer muscle reperfusion times, especially for the upper-extremity muscles.

Though many studies have provided detailed descriptions of DP (and other XC-skiing sub-techniques), few have aimed to understand the nature of DP in more fundamental terms in which general mechanical and energetic principles can be discerned. For example, exactly how much of P_{mean} is originating at the upper- and lower-extremities and how such a relationship is influenced by incline-speed combinations and/or intensity is not clear. Studying, for example, mechanical energy fluctuations in DP (and other XC-skiing sub-techniques), and compare such mechanics with other locomotions, may help us to understand the underlying principles of propulsion mechanics. Thereby, one may be able to explain why skiers move as they do, instead of simply describing how they move. From such information, one might be better able to explain differences between skiers of different performance levels and aid coaches and skiers to enhance performance of all skiers as well as to explain – on mechanical and energetic terms – why, for example, DIA is preferred over DP at steeper inclines and vice versa.

Mechanics of double poling

Recently, Kehler et al. (2014) studied mechanical energy fluctuations in DIA. Though the energy fluctuations were similar to those characterizing running, they concluded that DIA is a mechanically unique movement since the decrease in kinetic energy, instead of being stored as

elastic energy in muscle-tendons as in running, is lost to rolling (or gliding) friction during the ski glide phase. Pellegrini et al. (2014) studied mechanical energy fluctuations in all classical sub-techniques. In DP, they found potential and kinetic energy to fluctuate out-of-phase throughout the cycle, concluding that DP resembles a pendular gait which characterises walking. This was somewhat surprising, as in DP any mechanism that would enable a ‘passive’ exchange between potential and kinetic energy by large seems absent.

Danielsen et al. (2015) subsequently used a similar approach to gain more insights into fundamental propulsion mechanics in DP. By having skiers DP on an ergometer, measurements of instantaneous fluctuations of external poling power could be separated from changes in body mechanical energy. It was found that, although DP shares some characteristics of both the inverted pendulum and spring-mass mechanisms in terms of energy fluctuations, DP is a biomechanically unique movement in which the decrease in body mechanical energy during the poling phase is used directly as propulsion power through the poles. Figure 2 shows how muscle power generated during the swing phase increases body mechanical energy (positive \dot{E}_{body}). In the poling phase, part of the decreasing E_{body} (negative \dot{E}_{body}) is directly transferred to poling power. Thus, work done by the lower-extremity during the swing phase can contribute (indirectly, via a transfer as body mechanical energy) to pole propulsion power. In that study it was estimated that $\sim 50\%$ of P_{mean} originates from lower-extremity muscle power during the swing phase. However, this value (work done during swing, presumably by lower-extremities) decreased slightly with intensity, which was in contradiction to what most studies have shown. This suggests that the lower-extremities do work during poling as well. To get better insight into the specific source of power generation during the poling and swing phases in DP, an inverse dynamics analysis is needed.

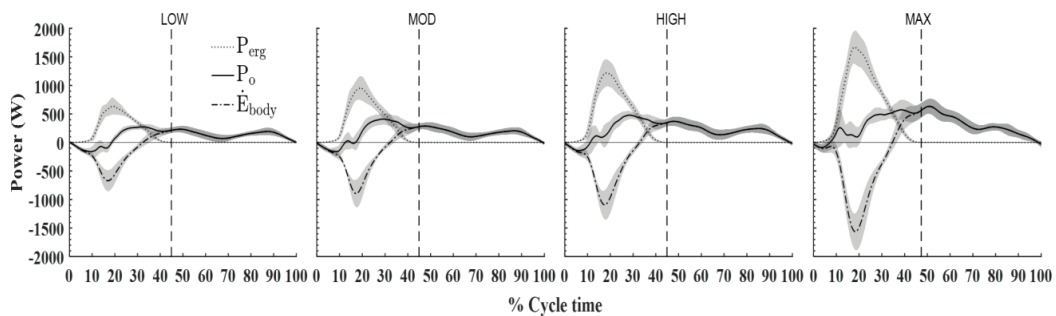


Figure 2 Fluctuations in external poling power (P_{erg} , i.e. power flow to the ergometer), the rate of change in total body mechanical energy (\dot{E}_{body}), and the sum of P_{erg} and \dot{E}_{body} which is total muscle power output (P_o) while ergometer DP at increasing intensities. Dashed vertical lines indicate end of the poling phase. Modified from Danielsen et al. (2015).

In (roller or on-snow) skiing the measurement of instantaneous propulsion power is somewhat ambiguous. For example, in a moving body on the level, the kinetic energy of the body includes energy associated with velocity increases due to propulsion power via the poles (acceleration). This is also true on an incline, where also potential energy changes include the continuous rise of the body along the incline, which is part of the external power as typically defined in locomotions (Cavagna et al., 1977; Fenn, 1930). No studies have investigated the relations between mechanical energy fluctuations and fluctuations in pole propulsion power while (roller or on-snow) skiing DP. Apart from furthering the understanding of fundamental principles involved in DP, such an investigation can provide insight into if and how lower body work contributes to propulsion power in skiing DP.

At the joint level, many studies have provided detailed descriptions of joint angle and angular velocity changes, especially the effect of increasing DP speed or intensity. However, the specific source of generation and destination of mechanical power in the poling and swing phases of DP is not clear. By assessing the net moment and mechanical power at each joint, an examination of the joint-specific work load and contribution to P_{mean} can be determined at different speeds and intensities. This may provide practically relevant information for coaches and skiers, since typically 80-90% of total training volume is low-intensity while races are at high-intensity. Moreover, by first having discerned more fundamental and basic whole-body dynamics (Danielsen et al., 2015), the role and mechanisms of specific joint dynamics may be better interpreted. For example, some studies have investigated possible stretch-shortening mechanisms of the upper-extremity extensor muscles during DP (Lindinger et al., 2009; Zoppirolli et al., 2013), but without considering joint power data. Thus, conclusions regarding such stretch-shortening activity are preliminary. The understanding of whether or not these muscles go through such stretch-shortening work loops and the possible energetic benefits from such behaviour can be improved if one includes whole-body and dynamics analysis. Additionally, in all terrestrial locomotion, there seems to be a strict limit in regard to the direction of the propulsive GRF. Ideally, to accelerate forward (propulsion) the propulsive GRF should be directed forward. However, it is usually of interest to avoid falling and to do so orthogonal forces and changes in body angular momentum must – on average – be zero. Thus, the total GRF must act more or less close to the CoM. Such a constraint obviously has an effect on muscle coordination generating the joint moments required for certain directions of the GRF (Jacobs et al., 1993; Jacobs & van Ingen Schenau, 1992a, 1992b; van Ingen Schenau, 1989). How this constraint is handled in DP and relates to propulsion has not been investigated.

It was mentioned that when the terrain becomes steeper, most skiers transition from DP to DIA. Whether this is because of the decrease in mean speed at steeper inclines or because of incline itself is not fully clear. Although Ettema et al. (2017) found incline to affect transitions more than speed, this was somewhat in contradiction to Pellegrini et al. (2013). At the same P_{mean} , Dahl et al. (2017) found that skiers prefer DP on 5% incline but DIA at 12% incline. Physiologically, these preferences corresponded to higher efficiencies (lower energetic cost) for the favoured sub-techniques at the respective inclines, where especially rate of perceived effort in the arms were much elevated for DP at 12% incline. Mechanically, the preferences found by Dahl et al. (2017) was coupled to larger fluctuations in instantaneous power (i.e., linked to how propulsive forces are generated) in DIA at 5% incline, which likely is coupled to the restricted ability (time limit) for effective ski propulsion. At 12% incline, results were less clear. For DP it was hypothesized that the ability to utilize leg work for propulsion power (Danielsen et al., 2015) may be restricted due to gravity-surface relation at steep inclines or that differences in arm work (more arm work at steep incline) play a role in disfavouring DP. Comparing fundamental propulsion mechanics and whole-body as well as joint dynamics in uphill DP (e.g., 5% and 12% inclines, where DP is still preferred over DIA at 5% but not at 12% incline (Dahl et al., 2017)) may help to answer some of these questions and further the understanding of DP technique execution.

Purposes

The overall purpose of this thesis was to study the energetics and dynamics of the DP sub-technique in classical style cross-country skiing. To do so, both whole-body and joint dynamics were investigated. In particular, the aim was to quantify the specific sources of generation and destination of mechanical energy in various DP conditions (e.g., upper vs. lower extremity).

Study **I** aimed to examine the effect of exercise intensity on joint power and dynamics in ergometer DP. This was the first study that examined the specific role of each joint in terms of power throughout the DP cycle. Based on previous studies showing that increasing DP intensity is governed mainly by increased lower-extremity involvement, it was expected that lower-extremity power contribution would increase. Attention was given to the role of a specific dynamic constraint, i.e., the requirement to control whole body angular momentum which is done by appropriately directing external forces, demanding certain joint moments and therefore powers.

Study **II** aimed to examine mechanical energy fluctuations and dynamics in level roller-skiing DP on a treadmill at increasing speeds. A similar approach was used as in Danielsen et al. (2015) where movement and propulsion mechanics were elucidated in ergometer DP. Dynamics of upper-extremity joints were also examined, and upper-extremity and lower-extremity and trunk power was calculated. Based on previous studies showing an increased lower-extremity – but not so much upper-extremity – involvement, it was hypothesised that the relative power contribution from the lower-extremities and trunk would increase with speed.

Study **III** aimed to investigate energetics and dynamics in uphill roller-skiing DP at different incline-speed combinations. In uphill skiing, DP is still preferred over DIA at slight inclines (e.g., 5%), but not at steep (e.g., 12%) inclines. This suggests that the capacity to effectively generate pole propulsion may be approaching some limit, which was examined in a dynamics and energetics perspective. It was expected that different boundary conditions (e.g., incline effect on gravity-surface relation) impose constraints on perpendicular body heightening and lowering, which may restrict the ability to use the lower-extremity and trunk as a source of propulsion power at steep incline and demand more upper-extremity power.

Methods

The methods presented here provide a summary of the methods used in the original papers which the reader is referred to for a more detailed description.

Participants

A total of 21 male Norwegian cross-country skiers competing at national and international level volunteered to participate. In study **I**, 9 skiers participated, while 14 participated in both study **II** and **III**, and two skiers took part in all three. The majority of the skiers competed at a high national and lower international level (e.g., Norwegian National Cup, Scandinavian Cup), while some were competing at a high international level (World Cup, World Championships and Olympics, including winning Olympic medals). All skiers signed written informed consent prior to participating and the study protocols were registered and approved by the Norwegian Social Science Data Services. The studies were conducted in accordance with the Declaration of Helsinki.

Protocols

In all studies general and/or specific warm-up was performed for ~20-30 min, including running (general) and DP (specific). In the main experiments in study **I**, the skiers performed DP on a DP ski ergometer, which consisted of three 4-min bouts of DP at steady-state submaximal exercise intensities. These intensities were matched internally, i.e., each skier was told to deliver a stable mean external power to the ergometer corresponding to a rate of perceived effort of ~10 (intensities: LOW), ~13 (MOD) and ~15 (HIGH) on the Borg scale (Borg, 1970). Afterwards, the skiers performed one 3-min closed-end (all-out) performance test (MAX). That is, the skiers were instructed to generate the highest possible mean power (over the 3 min period). In all tests the skiers were instructed to keep their self-selected CR stable.

In study **II and III**, skiers performed roller-skiing DP on a large treadmill. In study **II**, they performed DP at three fixed speeds (15, 21 and 27 km·l⁻¹) at 1% inclination. These speeds typically represent low-, moderate- and high-intensity DP as performed in daily training, though speed typically is lower outdoors at the corresponding intensities due to wind resistance (and differences in rolling resistance or snow friction). In study **III** the treadmill was set at 5% and 12% inclines and the speeds were 9.3, 12.4 and 15.5 km/h at the former and 4.7, 6.4 and 7.9 km/h at the latter incline. At the two inclines these specific speeds elicited an increase in work rate of ~50 W between each speed, while work rate was the same at both inclines (thus

excluding the effect of work rate when comparing effects of incline-speed combinations). During all treadmill experiments the skiers were told to remain approximately in the same position on the treadmill and to keep their self-selected CR (at each speed) stable.

Measurements, instruments and materials

Figure 3 depicts an overview of the experimental setup used in this thesis. In all studies, a minimum of 7 Oqus infrared cameras (Qualisys 400, Qualisys AB, Gothenburg, Sweden) were

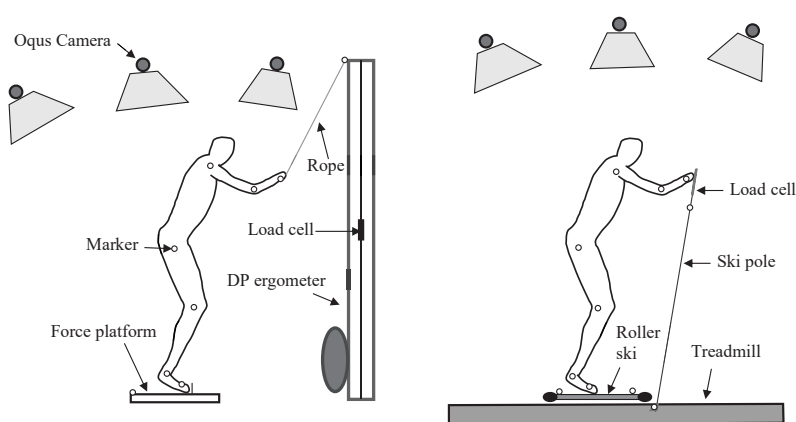


Figure 3 Overview of experimental setup in study **I** (left) and study **II** and **III** (right).

placed around the skiers to capture three-dimensional position characteristics of passive reflective markers. These markers were placed at anatomical landmarks defining the endpoints of body segments, thus tracking body movements. In study **I** a force platform (Kistler 9286BA, Kistler Instrumente AG, Winterthur, Switzerland) placed on the floor measured the lower-extremity ground reaction forces and a load cell (Futek Miniature Tension and Compression Load Cell, Futek Inc., Irvine, CA, USA) mounted in series with the drive cord inside the DP ergometer measured poling forces. All force data in study **I** were sampled at 500 Hz while kinematics were sampled at 100 Hz, and kinetics and kinematics were synchronized and stored on a PC using Qualisys Track Manager software. The DP ergometer is a commercial available Concept2 SkiErg (Concept2 Inc., Morrisville, VT, USA) that was mounted to the wall. In all tests the aero-resistance was set at the lowest level. This ergometer is frequently used by skiers in their daily training routines, and the essential technique characteristics of skiing and

ergometer DP has been shown to be similar (Halonen et al., 2015). In study **II** and **III**, roller-skiing DP was performed on a 5 x 3 m motor driven treadmill (Forcelink Technology, Culemborg, The Netherlands). The skiers in this thesis were all familiarised with treadmill roller-skiing from previous testing sessions and daily training routines. The same pair of roller skis were used by all skiers (resistance category 2, IDT Sports, Lena, Norway). The skiers chose poles of preferred length (Madshus UHM 100, Madshus, Biri, Norway) which were available in 5 cm increments. The tip of the poles (most distal point) were instrumented with special carbine tips to ensure good grip between the poles and the treadmill surface that is covered with non-slip rubber. During all treadmill sessions the skiers were secured with a safety harness connected to an emergency break. Both poles were equipped with load cells (CDF Miniature Button Load Cells, Applied Measurements LTD, Aldermaston, Berkshire, UK). The load cells measured the axial (resultant) forces directed along the poles. In study **II** and **III** force data were sampled at 1500 Hz and kinematics at 250 Hz. Pole force data were recorded via a telemetric system (TeleMyo DTS, Noraxon Inc., Scottsdale, AZ, USA) and synchronized with kinematics, and both were stored on a PC using Qualisys Track Manager software. In all cases, the skiers spent the first ~30 s of each bout of DP to achieve a steady-state mean power output and CR before data were collected for ~75-90 s of each bout. The skiers did not know when data were collected.

Analysis

To remove high-frequency noise, in study **I** dynamic and kinematic signals were digitally low-pass filtered at 50 Hz and 25 Hz, respectively. In ergometer DP there are no rapid impact forces and body movements are rather smooth. Thus, choosing different cut-off frequencies did not affect further calculations as visually checked by using different (including similar) cut-off values (Bisseling & Hof, 2006; van den Bogert & de Koning, 1996). In roller-skiing DP, impact forces occur as the poles make contact with the treadmill belt, and therefore some body movements are more abrupt. In study **II** and **III** dynamic and kinematic signals were low-pass filtered with the same cut-off frequency of 15 Hz. In all cases, an 8th order, zero-lag (bi-directional application), Butterworth filter was used.

A similar rationale and thus analysis was used in all three studies. The body of the skier is approximated as a system of rigid linked segments connected by frictionless revolute joints (Figure 4). Position of CoM of each segment and of the whole body CoM was calculated using individual body mass and segment lengths according to the equations provided by de Leva (1996) and Winter (2009). The segment lengths were determined as the average length over the

entire period of analysis. Linear and angular velocities and accelerations of joint angles and segments and whole body CoM were calculated by numerical differentiation. In study I, markers placed on the rope continuously tracked rope angle and displacement (i.e., length changes between marker placed on the handle and marker placed on the ergometer body at the point where the ropes enter the ergometer). From this, instantaneous absolute rope velocity was obtained. Multiplication of poling force (F_{poling}) with this velocity yielded instantaneous poling power delivered to the ergometer (P_{erg}).

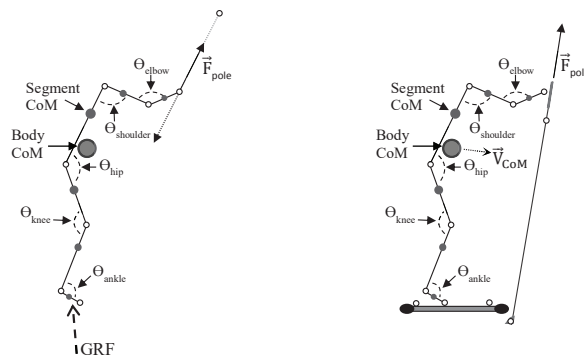


Figure 4 Illustration of body segments and their endpoints which are defined by markers. These segments are foot, shank, thigh, trunk (including head), upper arm and forearm (including hand). The dark shaded dots on each segment represent segment CoM, while light shaded dot illustrates whole-body CoM. Definition of joint angles (Θ) and measured external forces in ergometer DP (left) and roller-skiing DP (right) are also shown.

In treadmill DP indoors there is no wind resistance and Equation 1 was written as:

$$P_{\text{mean}} = v(mg \sin \alpha + (mg \cos \alpha - \bar{F}_{\text{pole}_\perp})\mu) \quad [2]$$

where v is treadmill belt speed (m/s), m is body mass including equipment (kg), g is gravitational acceleration ($9.81 \text{ m}\cdot\text{s}^{-2}$), α is angle of treadmill inclination (rad), $\bar{F}_{\text{pole}_\perp}$ is cycle average perpendicular component of F_{pole} (N) and μ is the coefficient of rolling resistance. In ergometer DP, P_{mean} is simply the cycle average P_{erg} . To address the purposes of this thesis the instantaneous power equation provided by van Ingen Schenau and Cavanagh (1990) was used. In ergometer DP (Danielsen et al., 2015) this equation was referred to as:

$$P_o = dE_{\text{body}}/dt + P_{\text{erg}} \quad [3]$$

where, dE_{body}/dt is the time rate of change of body mechanical energy and P_{erg} is the rate of energy flow to the environment. In study **I** net moments about the joints depicted in Figure 4 were calculated using standard inverse dynamics (Elftman, 1939; Winter, 2009). Multiplication of joint moment with angular velocity gave joint power. The summed joint power equals P_o by rule. However, when applying Equation 3 to the data, the summed joint power did not equal the right hand side of Equation 3, resulting in a rest power not accounted for. This was to be expected because of considerable within-trunk movements (flexion and extension) while this was neglected in the inverse dynamics analysis due to the inherent problem in obtaining reliable moment data about the non-rigid trunk in DP. Therefore, a rationale similar to the one used by Zelik and Kuo (2012) and Riddick and Kuo (2016) was applied. The difference between the summed joint power (elbow+shoulder+hip+knee+ankle) and P_o was defined as trunk power. To address the issue of the requirement to control angular momentum by appropriate direction of GRF (and F_{poling}) and how this is associated with net joint moments, the moment generated about CoM by F_{poling} and GRF was calculated together with their sum (net moment about CoM).

In treadmill DP (study **II** and **III**) Equation 3 was written as:

$$P_o = dE_{\text{body}}/dt + P_{\text{roll}} \quad [4]$$

where P_{roll} , the instantaneous power used to overcome rolling resistance, was estimated as:

$$P_{\text{roll}} = (mg \cos \alpha - \bar{F}_{\text{pole}_\perp}) \mu v_{\text{CoM}\parallel} \quad [5]$$

In all studies the instantaneous mechanical energy of the body was calculated as the sum of translational and rotational kinetic and gravitational potential energy of all segments (Winter, 1979, 2009):

$$E_{\text{body}} = \sum_{i=1}^N \frac{1}{2} m_i v_i^2 + \sum_{i=1}^N \frac{1}{2} I_i \omega_i^2 + \sum_{i=1}^N m_i g h_i \quad [6]$$

where m is segment mass (kg), v is segment absolute velocity (m/s), I is segment rotational moment of inertia ($\text{kg}\cdot\text{m}^2$), ω is segment angular velocity (rad/s), g is gravitational acceleration ($9.81 \text{ m}\cdot\text{s}^{-2}$) and h is segment height (m) above the reference datum. In study **I** the reference datum was the ground floor. In study **II** and **III** the reference datum was the centre of the moving treadmill belt and hence v is then the absolute velocity and h is the height relative to the coordinate system moving with treadmill belt speed (van Ingen Schenau, 1980).

In treadmill DP, P_o includes power associated with changes in body movements in goal-direction plus frictional losses on one hand (P_{\parallel} , the ‘external’ power) and on the other hand the rate of energy changes (mainly potential and kinetic) associated with movements perpendicular to the treadmill surface ($\dot{E}_{\text{body}\perp}$, the ‘internal’ power). In ergometer DP the definitions of external power (P_{erg}) and (internal) rate of body energy changes (E_{body}) are found in separate entities of measurement and thus unambiguous. In treadmill DP, $\dot{E}_{\text{body}\perp}$ (approximately equivalent to \dot{E}_{body} in ergometer DP) was estimated as:

$$\dot{E}_{\text{body}\perp} = P_o - P_{\parallel} \quad [7]$$

where P_{\parallel} was approximated using Equation 2:

$$P_{\parallel} = v_{\text{CoM}\parallel} (mg \sin \alpha + (mg \cos \alpha - \bar{F}_{\text{pole}\perp})\mu + ma_{\text{CoM}\parallel}) \quad [8]$$

with $a_{\text{CoM}\parallel}$ being the acceleration of CoM parallel to treadmill belt. As mentioned, the poles are the only source of propulsive power in DP. Instantaneous pole propulsion power was defined as:

$$P_{\text{pole}} = \bar{F}_{\text{pole}} \bar{V}_{\text{CoM}} \cos \beta \quad [9]$$

where \bar{F}_{pole} is the pole force vector (the direction of which was determined from the pole markers), \bar{V}_{CoM} is the velocity vector of the CoM and β is the angle between these two vectors. In the moving coordinate system, the point of application of F_{pole} does not move. Hence, P_{pole} is not a proper measure of power as defined in mechanics, i.e., force times velocity in the direction of force application. P_{pole} is equivalent to the instantaneous external mechanical power as defined in walking and running (Donelan et al., 2005; Kuo et al., 2005) where also no true

mechanical power is done against an external resistance (neglecting air resistance and shoe-surface deformations). Averaged over a cycle, P_{pole} should be equal to P_{mean} and cycle average P_o .

Inverse dynamics was also used in study **II** and **III** to obtain shoulder and elbow joint power. The lack of measurements of ski force and its point of application excluded the possibility for reliable lower-extremity joint moment data. Therefore, the residual between P_o and upper-extremity power (elbow plus shoulder power, P_{UE}) was defined as trunk+lower-extremity power (P_{TLE}).

In study **I**, the beginning of each DP cycle was defined as the shortest length of the ropes. The poling phase was defined as from the start of the cycle to the longest length of the ropes, with the rest being the swing phase. In treadmill DP, the cycle began at pole plant, poling phase was the period when the poles were in contact with the surface and the swing phase when the poles were in the air.

All signals (e.g., kinematics, dynamics, energies) were time normalized over each cycle and ~20 movement cycles for each skier were used to generate group means and 95% confidence interval (CI) time traces. Individual means were used to generate specific group mean variables. These included absolute and relative power values, averaged over the duration of the poling phase, the swing phase and the whole cycle. Thereby, the relative contribution from specific power sources (e.g., joints, upper or lower extremity) to P_{mean} was obtained.

Statistics

All data were found to be approximately normally distributed by inspection of normal Q-Q plots and histograms. Level of significance was set to 0.05. To evaluate the effect of intensity in study **I**, speed in study **II** and incline-speed combinations in study **III**, two-way and one-way analysis of variance for repeated measures was performed. Contrasts testing for differences between adjacent intensities (Fisher least significant difference) and paired t-tests were used as *post-hoc* analysis. All statistical tests were performed in SPSS version 24 (IBM Inc., Armonk, NY, USA) and Microsoft Excel version 14.0.7190.5000 (Office 2016, Microsoft Corporation, Redmond, WA, USA).

Results

Study I

This study investigated the effect of intensity on joint power and dynamics in ergometer DP and the main question was whether the contribution from the lower extremity joints would increase or decrease with increasing intensity. Nine skiers performed DP on a DP ergometer while body kinematics and dynamics were obtained. Joint moments and powers were calculated and the role of the joints in handling the demand of increasing P_{mean} across intensities were examined while taking the specific dynamic constraint of controlling whole body angular momentum changes by appropriate joint coordination into account.

P_{mean} (reflecting power against the ergometer's resistance) was 116 ± 10 , 166 ± 22 , 214 ± 25 and 306 ± 25 W. Cycle rate increased progressively with intensity, from .74 Hz at LOW to .97 Hz at MAX, while poling time decreased from .62 s at LOW to .49 s at MAX (all $P < .05$). Relative poling time (% of cycle time) was ~45% at LOW, MOD and HIGH, before increasing to 47% at MAX ($P < .05$).

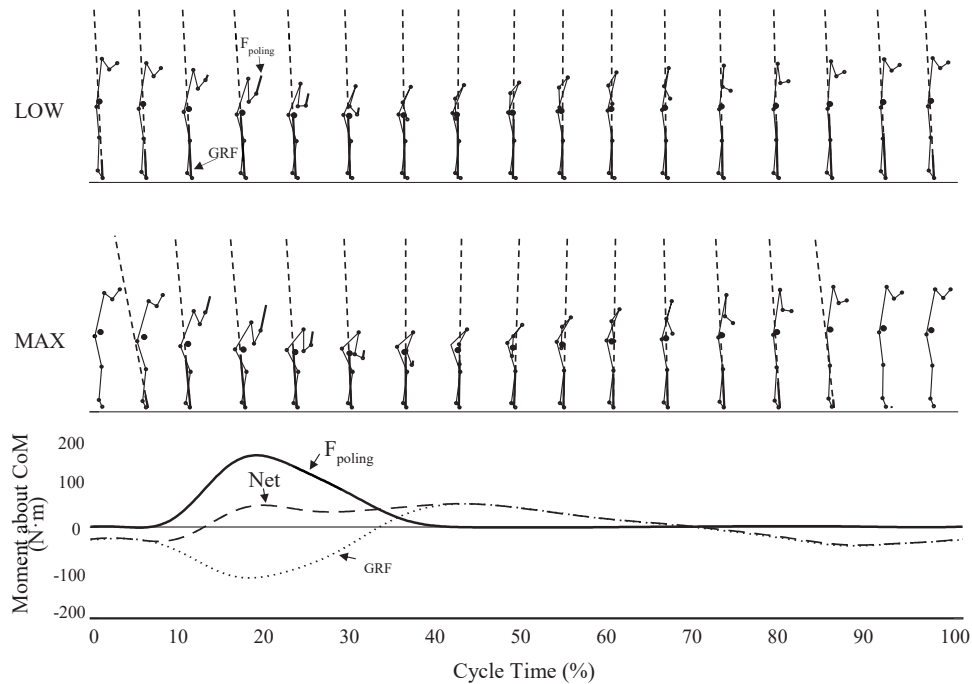


Figure 5 Stick diagram of one representative skier while ergometer DP at LOW and MAX intensities. The dashed GRF better illustrates the line of action. The lower diagram shows the moment generated about the CoM by the action of F_{poling} and the GRF at intensity HIGH (mean of all skiers).

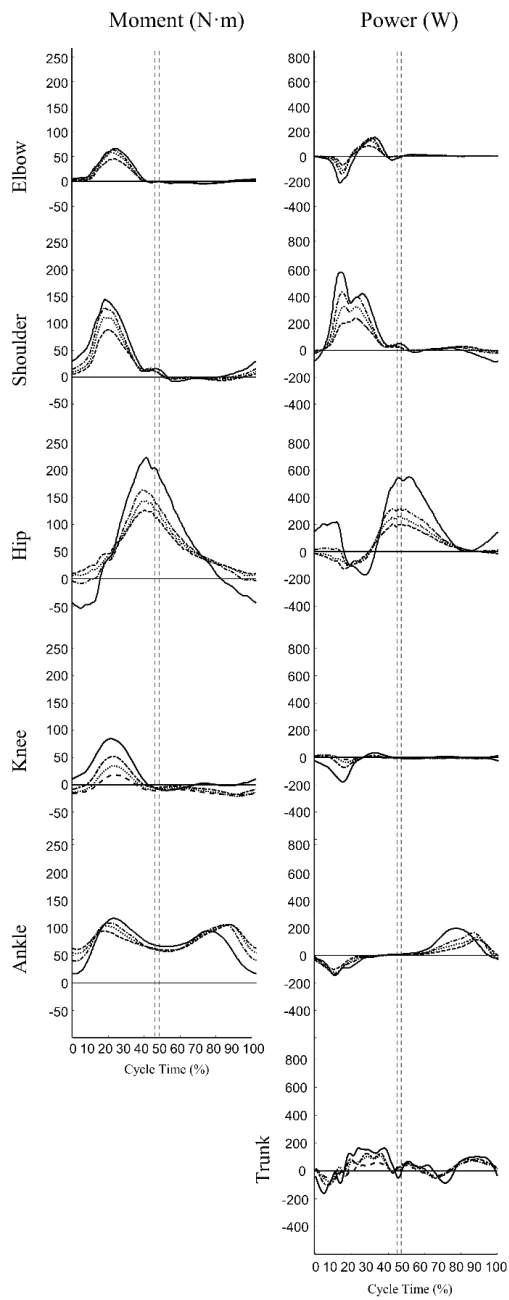


Figure 6 Joint moment and power at increasing intensities while ergometer DP (mean of all skiers). Positive moments indicate an extending moment while negative moments indicate a flexing moment. Dashed vertical lines indicate end of poling phase at LOW, MOD and HIGH (left) and MAX (right).

Figure 5 shows the line of action of F_{poling} and the GRF while ergometer DP and the moment these forces generated about CoM. Generation of F_{poling} (and thereby P_{erg}) induce a backward rotating moment which (on average) must be balanced by a forward rotating moment induced by the GRF.

Figure 6 shows the net moment and power about generated at the joints. Across intensity, both net joint moments and powers increased rather progressively, with the exception of the hip joint in which an extensor moment was dominating throughout the cycle at LOW and MOD, changing into a flexing moment at HIGH and especially MAX at the very beginning and end of the cycle. This is also reflected in a burst of substantial positive hip power in the swing-to-poling transition period.

Average joint power over the entire cycle, and over the poling and the swing phases are shown in **Table 2**. During the poling phase, the shoulder generated most power. Shoulder power rapidly increased from the onset of poling, the peak coinciding with peak F_{poling} and the peak in negative elbow power. As intensity increased, hip power became substantial, due both to the positive burst during the swing-to-poling transition phase and to the large positive power during the poling-to-swing transition (body heightening initiated). Elbow power was both negative and positive during the poling phase, with mean elbow power being positive from LOW to HIGH, and negative at MAX. Ankle (and knee) power showed a distinct negative period at the beginning of poling at all intensities, and a period of ankle power generation occurred towards the end of the swing phase.

During the swing phase, no P_{erg} is generated and upper-extremity power is negligible. The trunk, hip and ankle generated considerable power in a proximodistal sequence, heightening and repositioning the body for the subsequent cycle. Here, hip power was largest, followed by ankle power and trunk power.

Over the entire cycle, most power was produced by the shoulder and hip at all intensities, with average hip power becoming larger than average shoulder power at MAX. Relative upper-extremity power (sum of elbow and shoulder) decreased with intensity (51, 47, 43 and 33% at LOW, MOD, HIGH and MAX, respectively), thus lower-extremity contribution increased from 37% at LOW to 54% at MAX ($P < .001$) while trunk contribution remained similar (~13%).

Table 2. Absolute (W) and relative (%) joint power while ergometer DP at increasing intensities. Values are mean \pm 95% CI, *P*-values for the repeated measures ANOVA [N = 9].

	Intensity				<i>P</i>
	LOW 116 \pm 10 W	MOD 166 \pm 10 W	HIGH 214 \pm 25 W	MAX 306 \pm 25 W	
Cycle (W)					
Ankle	6 \pm 3	9 \pm 4	13 \pm 6	22 \pm 7	<0.001
Knee	-2 \pm 3	-3 \pm 4	-7 \pm 4	-20 \pm 7	<0.001
Hip	38 \pm 7	58 \pm 7	84 \pm 10	164 \pm 16	<0.001
Shoulder	52 \pm 10	69 \pm 13	85 \pm 17	104 \pm 21	<0.001
Elbow	6 \pm 6	8 \pm 9	7 \pm 9	-1 \pm 13	0.020
Trunk	15 \pm 6	25 \pm 12	31 \pm 10	39 \pm 12	0.001
Cycle (%)					
Ankle	5 \pm 2	5 \pm 3	6 \pm 3	7 \pm 2	0.022
Knee	-2 \pm 3	-2 \pm 2	-3 \pm 2	-7 \pm 2	<0.001
Hip	33 \pm 7	37 \pm 8	40 \pm 5	54 \pm 6	<0.001
Shoulder	45 \pm 6	42 \pm 6	40 \pm 6	33 \pm 5	<0.001
Elbow	6 \pm 5	5 \pm 5	3 \pm 4	0 \pm 4	<0.001
Trunk	13 \pm 6	14 \pm 6	14 \pm 5	12 \pm 4	0.769
Poling (W)					
Ankle	-33 \pm 11	-41 \pm 13	-46 \pm 14	-45 \pm 13	0.014
Knee	0 \pm 4	-3 \pm 3	-11 \pm 4	-40 \pm 7	<0.001
Hip	0 \pm 14	19 \pm 14	47 \pm 18	123 \pm 26	<0.001
Shoulder	104 \pm 20	145 \pm 30	185 \pm 37	232 \pm 47	<0.001
Elbow	12 \pm 12	16 \pm 19	14 \pm 21	-7 \pm 28	0.006
Trunk	5 \pm 13	28 \pm 26	29 \pm 16	45 \pm 26	<0.01
Swing (W)					
Ankle	39 \pm 15	50 \pm 19	62 \pm 22	83 \pm 19	<0.001
Knee	-4 \pm 4	-4 \pm 5	-3 \pm 7	-3 \pm 7	0.888
Hip	71 \pm 17	90 \pm 17	116 \pm 20	200 \pm 35	<0.001
Shoulder	10 \pm 6	7 \pm 7	3 \pm 8	-13 \pm 9	<0.001
Elbow	1 \pm 1	2 \pm 1	2 \pm 1	4 \pm 1	0.003
Trunk	24 \pm 8	23 \pm 13	33 \pm 15	34 \pm 18	0.293

Study II

This study examined the effect of increasing speed on mechanical energy fluctuations and propulsion mechanics in treadmill DP on the level. Skiers performed treadmill DP at 1% incline at low, moderate and high speeds (15, 21 and 27 km/h). Kinetic (E_{kin}), potential (E_{pot}) and total (E_{tot}) body mechanical energy were calculated, as was the rate of change of body energy perpendicular to the treadmill surface (perpendicular to goal-direction, $\dot{E}_{body_{\perp}}$). $\dot{E}_{body_{\perp}}$ was expected to be out-of-phase with pole propulsion power (P_{pole}), indicating a direct transfer of part of $\dot{E}_{body_{\perp}}$ (energy generated by the lower extremity) to P_{pole} . Upper-extremity and lower-extremity and trunk power was also calculated, and it was expected that the contribution from the lower extremity and trunk would increase with increasing speed.

Table 3 shows the most essential cycle characteristics obtained during treadmill DP at increasing speeds. P_{mean} (mostly reflecting power against rolling resistance) increased by ~ 40 W between speeds. Both cycle rate and length increased with speed, while (both absolute and relative) poling time decreased. Swing time was less affected. The perpendicular displacement of the CoM increased with intensity, which was mostly due to an increased amount of body lowering during the poling phase and not due to maximal heightening during the swing phase.

Table 3. Basic kinematic and dynamic variables associated with treadmill DP at increasing speeds. Values are mean \pm 95% CI, P -values for the repeated measures ANOVA [N = 14]. All adjacent intensities were significantly different ($P < 0.05$).

	Intensity			P
	Low 15 (km/h)	Mod 21 (km/h)	High 27 (km/h)	
P_{mean} (W)	98 \pm 5	138 \pm 7	176 \pm 8	<0.001
Cycle rate (Hz)	0.72 \pm 0.02	0.75 \pm 0.02	0.81 \pm 0.03	<0.001
Cycle length (m)	5.76 \pm 0.18	7.74 \pm 0.24	9.21 \pm 0.41	<0.001
Poling time (s)	0.45 \pm 0.02	0.35 \pm 0.02	0.29 \pm 0.01	<0.001
Relative poling time (%)	32 \pm 1	26 \pm 1	23 \pm 1	<0.001
Swing time (s)	0.94 \pm 0.04	0.99 \pm 0.04	0.95 \pm 0.05	0.034
Max CoM height (m)	1.10 \pm 0.02	1.12 \pm 0.02	1.15 \pm 0.02	<0.001
Perpendicular CoM displacement (m)	0.14 \pm 0.01	0.19 \pm 0.01	0.26 \pm 0.02	<0.001

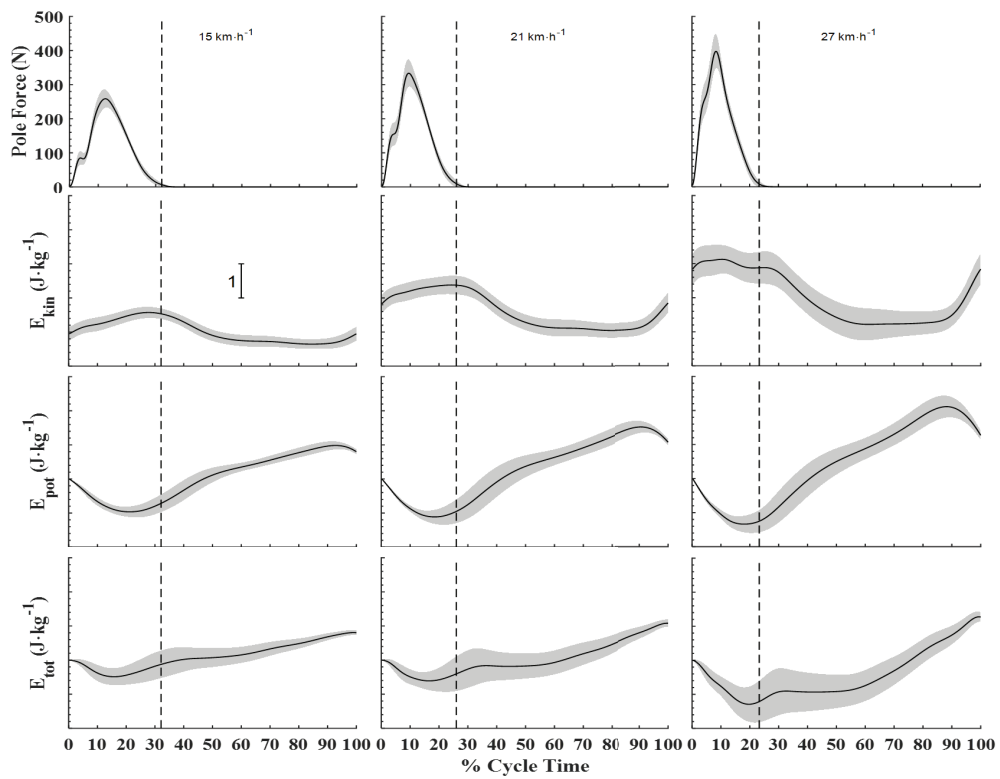


Figure 7 Pole force and mechanical energy against normalized cycle time during treadmill DP at increasing speeds. Traces are mean of all skiers [N=14] with 95% CI. Dashed vertical lines represent end of the poling phase. Vertical bar indicating $1 \text{ J} \cdot \text{kg}^{-1}$ applies to all diagrams.

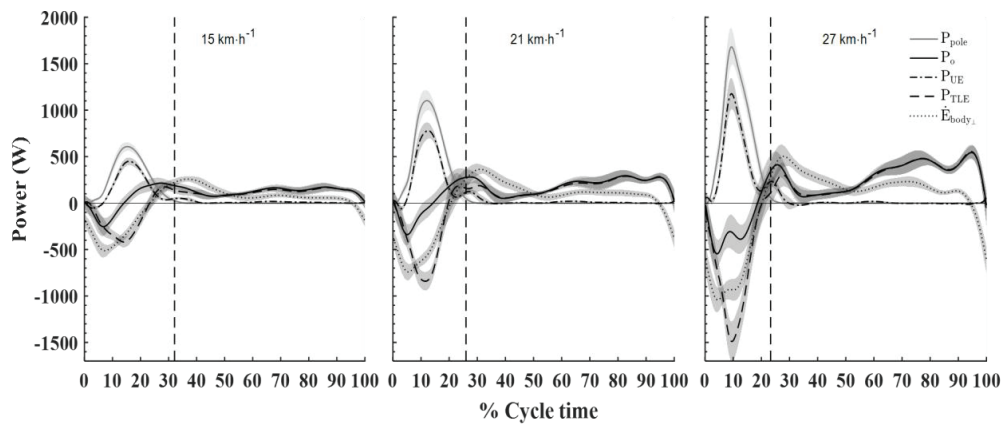


Figure 8 Mechanical power against normalized time during treadmill DP at increasing speeds. Traces are mean of all skiers (N=14) with 95% CI. The dashed vertical lines indicate end of the poling phase.

Figure 7 shows mechanical energy fluctuations and pole force while Figure 8 shows fluctuations in mechanical power. The repetitive heightening and lowering of the body throughout the cycle is reflected in the fluctuations in E_{pot} , which increased during swing (body heightening) and decreased during poling (body lowering). With increasing speed, the rate of decrease in E_{pot} was higher, which is reflected in an increase in E_{kin} towards the end of swing. Body lowering was finished slightly before the end of poling at all speeds. E_{kin} and E_{pot} fluctuated out-of-phase both during poling and swing. Because the magnitude of decrease in E_{pot} was higher than the increase in E_{kin} during poling, E_{tot} decreased during poling, with the decrease lasting longer at the fastest speed. The decrease in E_{pot} and E_{tot} during poling is reflected in the negative \dot{E}_{body_L} (Figure 8), which generally fluctuated out-of-phase with P_{pole} during poling. The pattern of power fluctuations remained largely similar across speeds. During poling, the upper extremity generated power while the lower extremity and trunk mostly absorbed power, before power generation occurred during the end of poling and for the majority of swing. The total muscle power was both negative and positive during the poling phase at 15 and 21 km/h. However, at 27 km/h, P_o showed a fundamental change, being mostly negative throughout the poling phase.

Table 4 shows average positive and negative power. Over the entire cycle, the upper extremity generated most power at all intensities (63% at LOW and 66% at MOD and HIGH speed, respectively). During the swing phase, the lower extremity and trunk generated increasingly more power, reflecting body heightening and repositioning. Within the poling phase, the upper extremity generated increasingly more power while the lower extremity and trunk absorbed increasingly more power. The work done during swing by the lower extremity and trunk amounted to 113 ± 15 J, 180 ± 19 J and 275 ± 20 J, while the amount of energy absorbed during the poling phase was -81 ± 11 J, -131 ± 14 J and -206 ± 17 J. Thus, the fraction of energy absorbed to that generated by lower-extremity and trunk work remained rather constant (~ 0.73).

Table 4. Absolute (W) and relative (%) power during treadmill DP at increasing speeds. Values are mean \pm 95% CI, *P*-values for the repeated measures ANOVA [N = 14].

	Intensity			<i>P</i>
	LOW 15 (km/h)	MOD 21 (km/h)	HIGH 27 (km/h)	
Cycle				
Upper extremity (W)	62 \pm 4	91 \pm 6*	115 \pm 8*	<0.001
Lower extremity and trunk (W)	37 \pm 4	47 \pm 7*	61 \pm 8*	<0.001
Upper extremity (%)	63 \pm 3	66 \pm 4*	66 \pm 4	0.016
Lower extremity and trunk (%)	37 \pm 3	34 \pm 4	34 \pm 4	
Poling				
Upper extremity (W ⁺)	176 \pm 15	327 \pm 31*	471 \pm 43*	<0.001
Lower extremity and trunk (W ⁺)	46 \pm 9	51 \pm 15	30 \pm 17*	0.014
Upper extremity (W ⁻)	-6 \pm 2	-6 \pm 2	-1 \pm 1*	<0.001
Lower extremity and trunk (W ⁻)	-182 \pm 25	-383 \pm 46*	-727 \pm 87*	<0.001
Swing				
Upper extremity (W ⁺)	12 \pm 1	15 \pm 1*	17 \pm 1	<0.01
Lower extremity and trunk (W ⁺)	122 \pm 19	184 \pm 23*	293 \pm 28*	<0.001
Upper extremity (W ⁻)	-1 \pm 0	-2 \pm 1*	-7 \pm 2*	<0.001
Lower extremity and trunk (W ⁻)	-1 \pm 1	-2 \pm 2*	-6 \pm 4*	0.013

W⁺ positive power; W⁻ negative power

* indicates significant different from previous speed (*P*<0.05)

Study III

This study examined the effect of incline-speed combinations on energetics and dynamics of uphill DP. Fourteen skiers performed uphill DP on a treadmill at three work rates at 5% (INC5) and 12% (INC12) inclines. The speeds at the two inclines were set to obtain equal work rates at both inclines. Upper-extremity power (P_{UE}) and lower-extremity and trunk power (P_{TLE}) was calculated from body kinematics and dynamics measurements, as was total muscle power output (P_o). Because of different boundary conditions due to incline, it was hypothesised that the relative P_{TLE} contribution would be lower at steep than at slight incline.

The speeds chosen at INC5 and INC12 gave a P_{mean} which increased by ~ 47 W between intensities at both inclines (Table 5). Cycle rate was higher at INC12 whereas work per cycle was higher at INC5. Both absolute and relative poling time decreased with speed at both inclines, but were higher at INC12 whereas swing time was lower at INC12. At INC12, peak pole force was larger and pole force was directed more backwards at pole plant. The amount of perpendicular displacement of the CoM over the cycle was quite similar, but still lower at INC5 at low intensity before this relationship reversed to high intensity.

Table 5. Kinematics associated with treadmill DP at different incline-speed combinations. Values are mean \pm 95% CI, P -values for the 2x3 repeated measures ANOVA [N = 14] where a, b and c indicates main effect of incline, main effect of speed, and interaction effect, respectively.

	Incline (%)	Work rate			P
		LOW	MOD	HIGH	
Speed (m/s)	5	2.58	3.43	4.31	
	12	1.33	1.77	2.21	
P_{mean} (W)	5	142 \pm 7*	189 \pm 9†	237 \pm 12†	0.294 ^a
	12	143 \pm 7	190 \pm 9†	238 \pm 11†	<0.001 ^b 0.520 ^c
Cycle Rate (Hz)	5	.84 \pm .03	.87 \pm .03*†	.89 \pm .03*†	<0.01 ^a
	12	.88 \pm .06	.93 \pm .04†	.97 \pm .03†	<0.001 ^b 0.125 ^c
Poling time (s)	5	.53 \pm .02*	.46 \pm .02*†	.40 \pm .02*†	<0.001 ^a
	12	.70 \pm .06	.61 \pm .03†	.54 \pm .03†	<0.001 ^b 0.124 ^c
Relative poling time (%)	5	44 \pm 1*	40 \pm 2*†	36 \pm 1*†	<0.001 ^a
	12	60 \pm 1	56 \pm 1†	52 \pm 2†	<0.001 ^b 0.592 ^c
Swing time (s)	5	.67 \pm .02*	.70 \pm .03*†	.72 \pm .03*†	<0.001 ^a
	12	.46 \pm .03	.47 \pm .02	.50 \pm .02†	<0.001 ^b 0.429 ^c
Peak pole force (N)	5	425 \pm 33*	506 \pm 39*†	562 \pm 41*†	<0.001 ^a
	12	534 \pm 35	570 \pm 37†	626 \pm 43†	<0.001 ^b <0.001 ^c
Pole angle at pole plant (°)	5	77.4 \pm 1.8*	78.3 \pm 1.8*	78.7 \pm 1.4*	<0.001 ^a
	12	69.2 \pm 2.3	69.4 \pm 1.8	69.7 \pm 1.8	0.181 ^b 0.359 ^c
Perpendicular CoM displacement (cm)	5	15.2 \pm 1.3*	19.2 \pm 1.4†	24.2 \pm 1.7*†	0.370 ^a
	12	16.7 \pm 1.6	19.8 \pm 1.8†	23.2 \pm 2.1†	<0.001 ^b <0.001 ^c

* significant difference between inclines and † significant difference from previous work rate ($P < 0.05$)

Figure 9 shows fluctuations in power. At both inclines, upper-extremity and lower-extremity and trunk power was negative during the first part of the poling phase during which the body is lowered. Lower-extremity and trunk power was generally more negative at INC5 and this period of negative power lasted longer into the poling phase at INC5 than at INC12. $\dot{E}_{body\perp}$ indicates the rate of body mechanical energy changes perpendicular to the surface, i.e., perpendicular body ‘lowering’ and ‘heightening’. The peak in negative $\dot{E}_{body\perp}$ was larger at INC5 (indicating faster body lowering) during the beginning of the cycle. $\dot{E}_{body\perp}$ becomes positive at about the same time as P_{TLE} , i.e., body heightening begins. Relative to pole off, this occurred earlier at INC12 than at INC5. $\dot{E}_{body\perp}$ and P_{TLE} were mostly positive for the remainder of the cycle, reflecting lower-extremity work which increases $E_{body\perp}$.

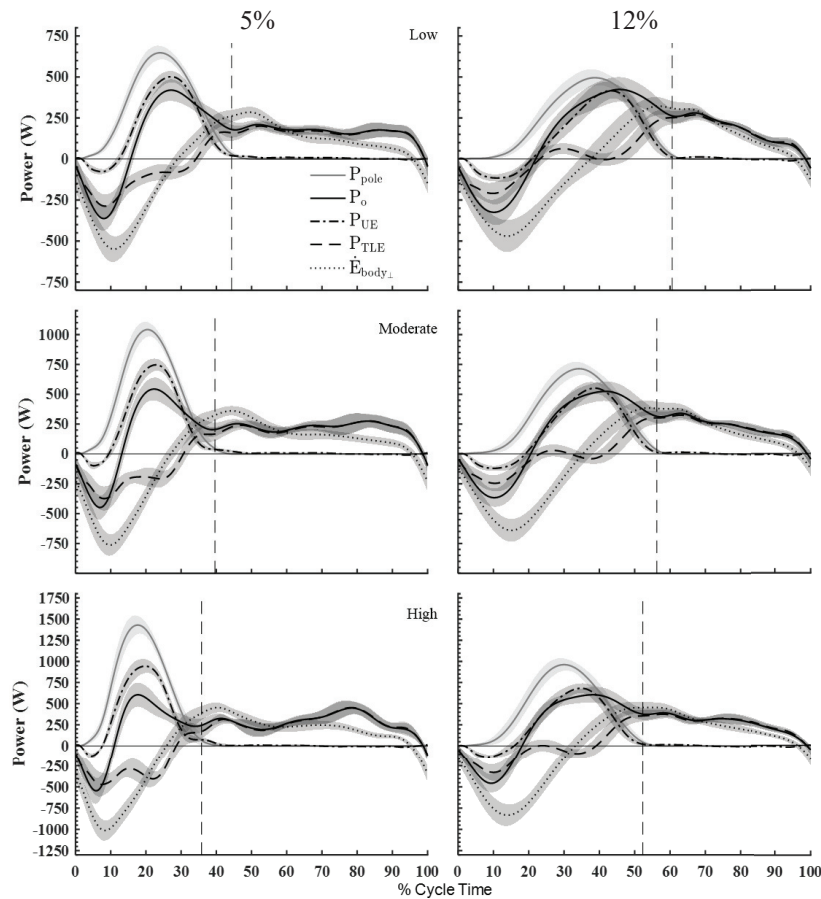


Figure 9 Mean (and 95% CI indicated by shaded areas) traces of pole power (P_{pole}), net muscle power output (P_o), upper-extremity power (P_{UE}) and lower-extremity and trunk power (P_{TLE}). The rate of energy changes associated with perpendicular body heightening and lowering ($\dot{E}_{body\perp}$) is also plotted. Dashed vertical lines indicate end of poling phase.

Over the entire cycle, both upper-extremity and lower-extremity and trunk power increased in proportion with work rate at both inclines (Figure 10). Thus, the relative power contributions were unaffected by work rate. The contribution from the upper extremity was larger at INC5 (63%) than at INC12 (54%) ($P<.001$).

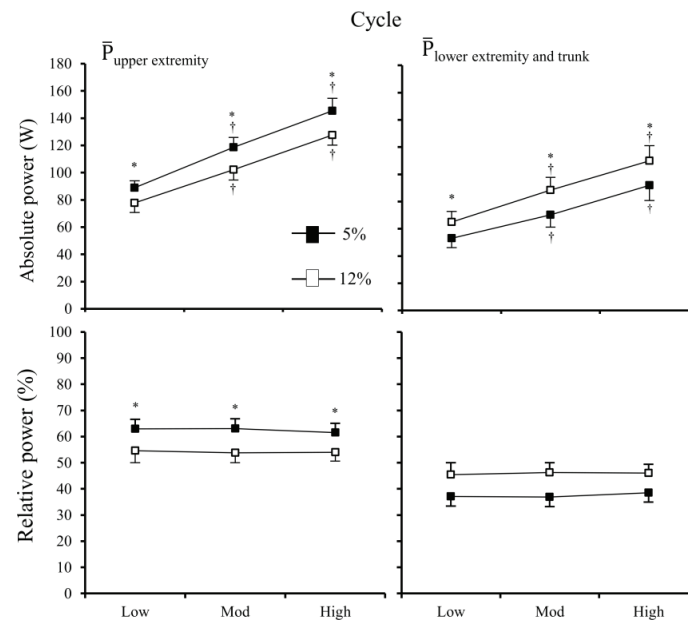


Figure 10 Cycle average power (\bar{P}) output about the upper extremity and lower extremity and trunk in uphill DP at different incline-speed combinations where work rate is the same at both inclines. Values are mean \pm 95% CI [N=14]. * indicates significant incline difference and † indicates significant different from previous work rate (both $P<0.05$)

Within the poling phase (Figure 11), the upper extremity generates considerable power at both inclines. The upper extremity generated increasingly more power at INC5 than at INC12 (interaction $P<.001$), while the lower-extremity and trunk generated more power at INC12 than at INC5 ($P<.001$). While upper-extremity power absorption is negligible, negative lower-extremity and trunk power is substantial and increasing considerably more with work rate at INC5 than at INC12 (interaction $P<.001$).

During the swing phase (Figure 12) the lower-extremity and trunk generate about an equal amount of power to heighten and reposition the body at both inclines.

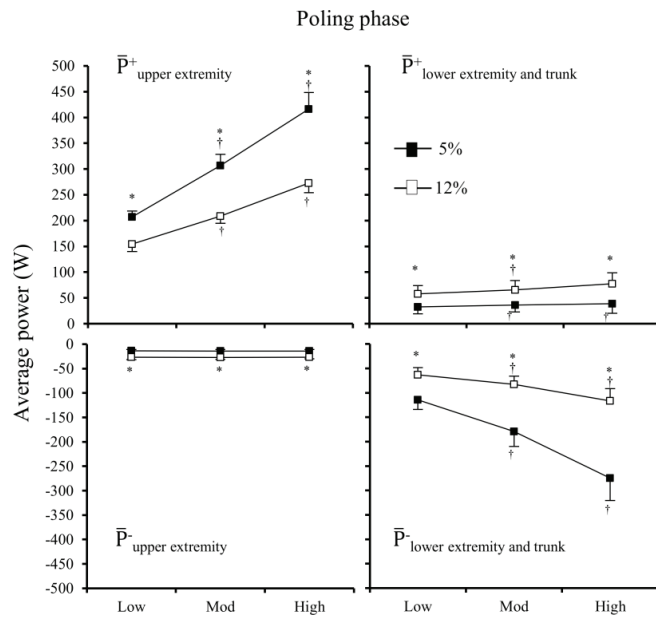


Figure 11 Average positive (\bar{P}^+) and negative (\bar{P}^-) power during the poling phase about the upper extremity and lower extremity and trunk while DP at different incline-speed combinations where work rate is the same at both inclines. Values are mean \pm 95% CI [N=14]. * indicates significant incline difference and † indicates significant different from previous work rate (both $P < 0.05$)

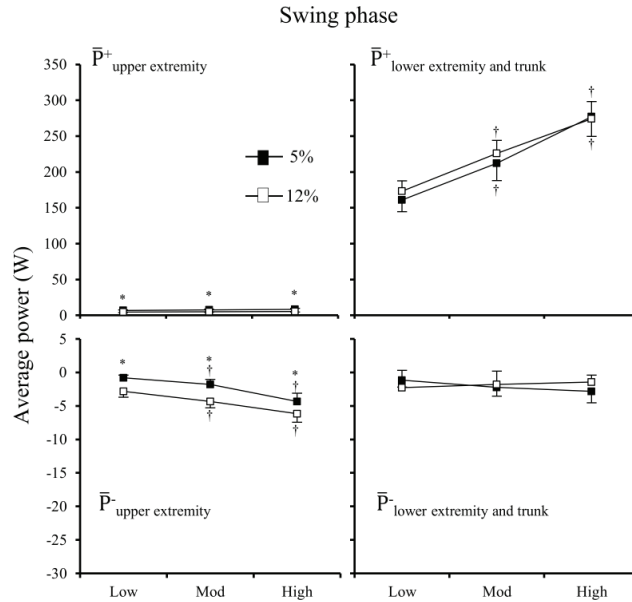


Figure 12 Average positive (\bar{P}^+) and negative (\bar{P}^-) power during the swing phase about the upper extremity and lower extremity and trunk while DP at different incline-speed combinations where work rate is the same at both inclines. Values are mean \pm 95% CI [N=14]. * indicates significant incline difference and † indicates significant different from previous work rate (both $P < 0.05$)

Discussion

This thesis provides novel information about the specific source of generation and destination of mechanical energy and of the role of specific joints in the dynamics of DP locomotion on level terrain, on uphill terrain at different incline-speed combinations and on an ergometer (which is frequently used in training). As expected, lower-extremity muscles mainly do work during the swing phase during which the body is heightened and repositioned while the poles are brought forward to the next point of contact with the ground. Although no propulsive force is applied during this action, muscle power output is considerable. During the following poling phase, the body is lowered and body mass is used to increase pole forces together with upper-extremity poling movements. Thus, work done by the lower extremity during the swing phase is temporarily 'stored' as body mechanical energy. Part of this energy is then directly transferred to pole propulsion power during the poling phase. The remainder may be reutilised through countermovement-like action. In roller-skiing DP, the upper extremity generates most of the pole propulsion power. In ergometer DP (study **I**) the upper-extremity contribution decreased from 51% at low intensity to 43% at high intensity, decreasing further to 33% at maximal intensity (3 min all-out test). In treadmill DP on the level (study **II**), the upper-extremity contribution was 63%-66%, while in uphill DP (study **III**) the upper-extremity contribution was 63% at slight incline and 54% at steep incline. From these values it follows that the lower extremity and trunk is a significant source of energy and power used as propulsion power in all DP conditions (ergometer, incline-speed combinations) investigated in this thesis.

Effect of intensity, speed and incline-speed combinations on power contributions

The effect of increasing exercise intensity on power contribution from the upper and lower extremities were examined in all three studies. Several previous studies have shown that when DP intensity is increased, skiers rely more on increased lower body than upper body involvement to increase total power output (P_{mean}) (Bojsen-Møller et al., 2010; Holmberg et al., 2006; Lindinger, Stöggl, et al., 2009; Rud et al., 2014; Zoppirolli et al., 2017). However, none of these studies examined this aspect in terms of joint work or power output. In ergometer DP (study **I**), the contribution from the upper extremity (elbow plus shoulder power) decreased from 51% at low intensity DP to 33% at maximal intensity DP (3 min performance test), which thus is in agreement with previous studies (e.g., Rud et al., 2014; Zoppirolli et al., 2017). In roller skiing DP on the level (study **II**), the upper-extremity contribution increased slightly from 63% at slow speed DP to 66% at medium and fast speed DP. Increasing speed while uphill

roller-skiing DP on slight and steep inclines (study **III**) had no effect on upper-extremity power contribution, which was 63% at 5% incline and 54% at 12% incline. In roller skiing DP, this means that average power output from both the upper and lower extremities (and trunk) increased more or less in proportion with increasing workload.

The finding of an increased contribution from the lower extremities in ergometer but not in roller-skiing DP is likely in part due to the presence of one extra mechanical degree of freedom in the ergometer DP setup, which is the option to regulate the direction of the GRF by use of horizontal frictional forces because the skiers remained in position on a full friction floor surface. The sign change in hip and partly knee moment during the swing-to-poling transition period is reflected in the line of action of the GRF changing from acting just in front of, to behind the hip and knee joint centres. Thus, the burst in positive hip power (and negative knee power) during the same time period is likely directly linked to this boundary condition, i.e., allowing for directing GRF variably, but keeping the total effect opposing to the backward rotation and forward pull by the ropes. Still, some of the positive hip power seen at the beginning of the poling phase may also be linked to a direct contribution to the generation of poling power by more active and faster trunk and hip flexion as a mean to increase poling force. In other words, the considerable ground friction makes the involvement of forceful trunk and hip flexion at onset of poling possible. In skiing DP (roller or on snow), horizontal ski forces are low and merely dictated by rolling resistance or gliding friction. In such a condition, the generation of the necessary moment arm for the (ski) GRF about CoM relies on appropriate adjustment of the vertical alignment between the point of force application and CoM. Alternatively, the positioning and direction of the poling force (i.e., the poles) is another option to control dynamic balance and angular momentum changes. Overall, (subtle) mechanical differences require modifications in coordination and joint dynamics that lead to energetic differences, i.e., generation and absorption of power. Despite these differences in energetics and dynamics, the kinematics by large seem very similar between the different modes of DP (see specific papers). A similar finding was found for imitation ski jumps from a fixed floor and from a rolling platform (Ettema et al., 2016).

The findings of no change in uphill DP (study **III**) and even a slight increase in level DP (study **II**) in upper-extremity contribution to P_{mean} is somewhat unexpected given the findings in previous studies (Bojsen-Møller et al., 2010; Rud et al., 2014; Zoppirolli et al., 2017) and in ergometer DP (study **I**). In ergometer DP, the largest change in joint-specific contributions occurred when P_{mean} was increased from 214 W to 306 W (high to max). In contrast, the highest work rates in level roller skiing DP was only 176 W, while in study **III** the

highest work rate was 237 W at both 5% and 12% incline. Thus, part of the reason for finding no essential change in relative power contribution in the roller skiing situations studied here may be that the work rates induced (or speeds) were too low to cause any essential changes. In this regard, it can be noted that this thesis did not study maximal sprint-like DP. When skiers engage in the very last 100-200 m mass spurts, they typically employ an even more jumping-like DP technique than those employed and studied at the highest intensities or speeds of this thesis. Thus, in the future it would be interesting to study, while measuring full dynamics (ski and pole forces), absolute maximal-intensity/speed DP technique. Moreover, the power contribution from the upper extremity was more similar between ergometer DP and uphill roller-skiing DP. This may likely be related to the more similar poling times, which are longer in ergometer and in steep uphill skiing DP where speed is lower than in level or slight uphill skiing DP. The main reason for the differences in intensity (speed) effects is, however, probably related to the mechanical difference regarding the potential use of horizontal GRF mentioned above, which affects muscle coordination and joint moment and power. Nevertheless, in terms of work and power, all three studies find that the lower extremity contribute substantially to power output in modern DP.

How does lower-extremity power contribute to propulsion power?

The way in which the lower extremity contribute to pole propulsion power were found to be similar to that which was described in a study on propulsion mechanics in ergometer DP (Danielsen et al., 2015). Both treadmill DP on the level (study II) and uphill (study III) induced comparable patterns in $\dot{E}_{\text{body}_\perp}$ fluctuation as in the ergometer situation (Danielsen et al., 2015). $\dot{E}_{\text{body}_\perp}$ was positive during most of the swing phase, meaning that E_{body_\perp} increased. Simultaneously, P_{TLE} was positive, meaning that the lower extremity and trunk generated power. While these studies could not separate this power into joint-specific sources, according to study I, most of this power is probably originating at the hip and ankle as well as at the trunk. Studies including measurement of ski forces and its point of application are necessary to further elucidate the role of specific lower-extremity joints while skiing DP. In joint power terms, these findings seem to correspond with electromyography studies. Holmberg et al. (2005) found higher activation levels in hip (gluteus maximus) and ankle (soleus and gastrocnemius) muscles than in for example the knee (quadriceps) muscles. In all studies, the power generation at the lower extremity (and trunk) during the swing phase increased more or less in proportion with workload. This is similar to the joint-specific powers obtained in study I. Although ankle and

hip power during the swing phase increased from 39 W and 71 W at low intensity DP to 83 W and 200 W at maximal intensity DP, respectively, there were no significant relative changes.

During the poling phase, more essential differences in dynamics between level and uphill, as well as between grades of steepness in uphill DP were found. During level treadmill DP, the lower extremity and trunk apparently absorbed considerable amounts of power during the short-lasing poling phase. Based on the joint-specific powers of study I, negative power occurred during the poling phase at the hip, knee and ankle, as well as some in the trunk. Accordingly, it seems as if all lower-extremity joints are responsible for the negative (net) lower-extremity power, however, future studies need to confirm this.

At the slight incline (5%), the amount of negative lower-extremity and trunk power was less, and became further reduced at steep incline (12%). Although the level treadmill DP situation cannot be directly compared to uphill DP on the two inclines since work rate was not the same, at first sight it can be suggested that the steeper the incline, less of the decrease in E_{body_\perp} is absorbed by the lower extremity and trunk. The decreasing E_{body_\perp} (negative $\dot{E}_{\text{body}_\perp}$) during the poling phase can only go to two sources, back to the muscle-tendon (lost as heat and/or temporarily stored as elastic energy) or to pole propulsion power. In study III it was hypothesized that on steep incline the possibility to use and transfer lower-extremity power to pole propulsion power is reduced because of different boundary conditions (Figure 13).

In level DP, force of gravity acts perpendicular to the goal-directed movement. Thus, all energy changes associated with body heightening and lowering is uncoupled to (external)

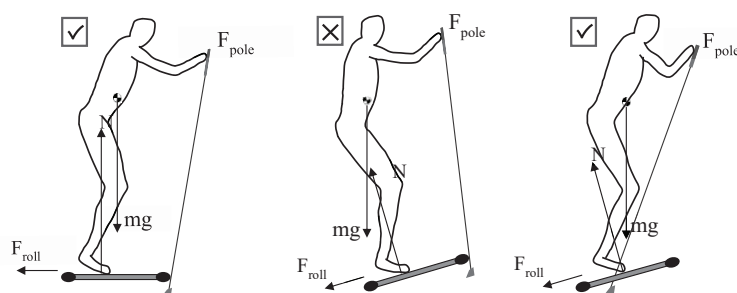


Figure 13 Level and inclined DP require different body and pole positioning in order to maintain dynamic force equilibrium. For example, if the same body and pole positioning as on the level (left) was to be obtained on an incline (middle), mg would generate a moment about base of support which would be hard to balance by F_{pole} or N . Therefore, the skier is forced to alter body and pole positioning relative to the surface (right).

goal-directed associated energy changes, a similar situation as in ergometer DP. In uphill DP, the body continuously moves up, so only body heightening and lowering perpendicular to the surface is uncoupled to external power. Achieving the same amount of perpendicular body heightening as in level DP becomes hard on steep inclines since the skier likely will be pulled out of balance by the external moment generated about base of support by force of gravity. To cope with the differences in external forces and to maintain balance, on an incline the skier alters body and pole positioning relative to the surface. Moreover, the steeper the incline the lower the normal force becomes and thus to maintain force equilibrium, pole force must (on average) be larger since the poles must support more of body weight (counteract the increased influence of the component of gravity parallel to the surface).

The peak in negative $\dot{E}_{\text{body}\perp}$ during the poling phase was largest at 1% incline (level) and lowest at 12% incline (steep uphill). In other words, the speed of perpendicular downward body movement is lowest at the steepest incline, implying that on steep incline less body energy may be available to be transferred into pole propulsion power. That the speed of downward body movement is lower at the steeper incline is also reflected in considerably longer poling times. At 1% incline, the perpendicular displacement of the CoM was 0.26 cm with a poling time (where most of body lowering occurs) of 0.29 s. At 12% incline the CoM displacement was 0.23 cm with a poling time of 0.54 s. Accordingly, it seems as if less body energy is available to be transferred to pole propulsion power, meaning that more power must be generated by the upper extremity at the steeper incline. This, however, is not the case. At 12% incline, the overall contribution from the upper extremity was ~54% which is lower than the ~63% contribution at 5% incline. This may be explained based on the different boundary conditions (Figure 13). At the steep incline, generation of large pole force over a longer time period is required. On less incline or on the level, generation of large pole force over a short time is not necessarily required (except at the very high speeds). That is, the athlete can choose to generate lower pole force over a longer time, which seem to require less extensive lower-extremity involvement over the cycle (Holmberg et al., 2005; Lindinger & Holmberg, 2011). At slight incline and level terrain, such a strategy seem to related to DP with increased cycle rates and shorter cycle lengths, which in turn is related to decrease in performance and efficiency (Holmberg et al., 2006; Lindinger & Holmberg, 2011; Sandbakk et al., 2010). However, the technical strategy actually used on slight incline and level terrain (i.e., generating large but short-lasting pole forces) apparently demands excessive body energy to be absorbed by the lower extremity and trunk during the poling phase. At steep inclines, the lower extremity must generate considerable power to rapidly heighten and reposition the body and poles during

a short swing phase, but this action comprises less energy. Thus, although less energy is available (due to incline effect on body movements and gravity-surface relation) at steep inclines, more of that energy is directly used as pole propulsion power and thus less excessive energy is absorbed.

Taken together, although the strategy of using the lower extremity seem to be of importance, a considerable amount of the energy generated by the lower extremity during the swing phase is absorbed by the lower extremity during the poling phase, especially in level treadmill DP (study II). This seems to be energetically ineffective. However, it may be argued that at slight inclines and on the level, the primary role of body heightening and lowering and associated lower-extremity power generation and absorption is, rather than contributing greatly to propulsion power, to set the body and poles in a condition in which the upper extremity can generate considerable power effectively. In level DP (~1-3% inclines), several studies have described the so-called preparation phase immediately preceding pole plant. This phase is characterized by a high hip – high heel position towards the very end of the swing phase in which the poles are swung forward to more than 90 ° relative to the ground before being planted close to 90 ° (backwards) at pole plant (Holmberg et al., 2005; Stöggl & Holmberg, 2011). During this phase (immediately before pole plant) especially upper-extremity extensor muscles show high activation levels, likely leading to higher muscle force levels (Holmberg et al., 2005; Lindinger et al., 2009). By preparing the body and especially the upper-extremity muscles for pole impact, it is likely that the higher muscle force levels (compared to no such preparation phase) at onset of poling lead to a greater capacity for muscle power generation since less time is used building up force(s). Interestingly, this preparation phase became less clear at 5% incline compared to 1%, and was non-existent at 12% incline. A similar finding was reported by Stöggl and Holmberg (2016) comparing level (1.7%) and inclined (12.3%) DP. However, although the kinematics of the preparation phase seem to disappear at steeper inclines, no studies have shown whether or not pre-activation of upper-extremity muscles also disappear and this needs to be further studied.

In a recent study based off the same data collection as in the present thesis, including the same skiers, Dahl et al. (2017) found that the skiers rated upper-extremity effort as (much) more demanding in DP at 12% than at 5% incline at the same work rate. Apparently, this rating of upper-extremity effort has little to do with the amount of power generated or work done by the upper extremity, since upper-extremity power generation was lower at 12%. As presented in study III, the magnitudes of elbow and shoulder moments were about the same at both inclines at all work rates, however the time of high muscle force generation (large joint moment

amplitudes) was longer at 12% incline (longer poling times). Although less work is done, this longer time period may lead to an increase in the metabolic cost of force generation (Dean & Kuo, 2011; Griffin et al., 1985; Roberts et al., 1998). Moreover, it may be directly linked to the increased sense of effort (Prilutsky & Gregor, 2001). The finding of similar joint moment magnitudes that lasts longer (lower angular velocities), but only some difference in mean upper-extremity power generation at steep incline, leads to the hypothesis that the upper-extremity extensor muscles may operate within a less favourable range of their force-length-velocity relationship. Overall, these findings suggest that the conditions for upper-extremity power generation (working condition) becomes less advantageous at the steeper inclines, which is linked to differences in body and pole positioning and in boundary conditions (Figure 13). These issues are likely playing a role in the transition and preference for DIA and not DP at these steeper inclines.

Another difference between level, slight and steep incline DP is the (much) shorter swing times on the steep incline. The shorter swing times (both in absolute time and as a percentage of cycle time) are likely connected to shorter muscle relaxation times, which previously has been discussed to induce a less fortunate hemodynamic situation, especially of upper-extremity muscles (Lindinger & Holmberg, 2011). This issue is likely related to the overall increased sense of effort in the upper extremity at steep inclines. The shorter swing times at steeper inclines were argued by Stöggl and Holmberg (2016) to be the main limiting factor for steep uphill DP, likely a part of causing factors for the lower preference for DP at steep inclines (Dahl et al., 2017). The main reason for shorter swing times on steeper inclines is most likely the increased influence of gravity parallel to the surface, which induces increasingly greater speed loss during the swing phase. In order to minimize this speed loss, poling time can be increased and/or swing time decreased, if cycle rate is kept similar. Cycle rate increased only little from INC5 to INC12, and the longer poling times at 12% versus 5% are mainly due to the lower speeds. The largest difference was in swing times, which is in agreement with Stöggl and Holmberg (2016). With regard to the short swing times, which also becomes shorter in DP on the level but at forced high cycle rates (Lindinger & Holmberg, 2011), several studies have discussed the enhanced demand upon timing and coordination, especially of the lower extremity and trunk during the swing phase. Since heightening and repositioning of the body and poles must occur faster this likely adds to the complexity of coordinating body movements, requiring highly developed motor skills (Lindinger et al., 2009). In study III, the lower-extremity power generation during the swing phase was similar at both 5% and 12%, but this power was generated over a longer time at 5%. Thereby, more work was done during the

swing phase at 5% incline and more time was available for the body to reach a higher (perpendicular) position towards the end of the swing phase through more pronounced lower-extremity extension movements. Consequently, the skiers shifted some of the body heightening action forward in time at INC12, which led to slightly more power generation by the lower extremity and trunk during the poling phase than at INC5.

Stretch-shortening and power transfer mechanisms

In previous studies examining electromyography together with kinematics it has been suggested that stretch-shortening in upper-extremity extensor muscles (the prime movers in DP) occurs as an essential characteristic of DP, especially when speed is increased (Lindinger et al., 2009; Zoppirolli et al., 2013). In study I, attention was given to this hypothesis. It was found that the flexion-extension movement of the elbow involves negative and positive power, however no such pattern was found for the shoulder where (only) positive power rapidly increased from onset of poling force generation. Moreover, the peak in negative elbow power (~200 W at MAX; Figure 6) coincided with the peak in positive shoulder power (~600 W at MAX). Because of these coinciding peaks in negative elbow and positive shoulder power, and because *m. triceps brachii caput longum* is a bi-articular elbow and shoulder extensor muscle, it was speculated that energy and power may be transferred by this muscle between the elbow and shoulder joint simultaneously as power is being transferred between the body, the upper extremity and to the ergometer ropes. Bi-articular muscles often show no relation to the angular displacement of the joints crossed. Rather, they play an important role in regulating and distributing the required net joint moments and power to achieve a certain direction of the external force and to distribute the total available power to the joints where it can contribute most effectively in doing work (Bobbert & van Ingen Schenau, 1988; Jacobs et al., 1993; van Ingen Schenau, 1989). Moreover, in ergometer DP there is a lack of a braking force at the onset of poling as the ropes are continuously pulled downwards and backwards.

In treadmill DP there is also no braking (pole) force present as the poles are directed backwards at pole plant (Stöggl & Holmberg, 2011). However, as the poles abruptly collide with the ground while the body is 'leaning over' the poles, there might be some work done upon the upper-extremity extensor muscles by the ground and poles, making stretch-shortening of these muscles more likely. In all treadmill DP situations, elbow power followed a somewhat similar pattern as in ergometer DP, with negative-positive power coinciding with flexion-extension movements. In level DP, negative shoulder power was negligible, and at the highest speed, positive shoulder power rapidly increased. During inclined DP, shoulder power was

more negative during prolonged flexion, especially at 12% incline. Compared to ergometer DP, however, in none of the treadmill DP situations did the (smaller) peak in negative elbow power coincide with the peak in positive shoulder power. Thus, differences in joint dynamics and (propulsive) poling force generation clearly exists between these different modes of DP although the kinematics are very similar. In addition to these findings and arguments, it is not evident that the poling movement contains a reversal or a countermovement of (part of) body mass, i.e., the athlete does not seem to be bouncing on his or her poles, which is a prerequisite for stretch-shortening cycle kind of muscle function. Rather, as the poles hit the ground, keeping the (upper) body quite rigid and stiff instead of compliant is emphasised in practice and seems to be of importance to immediately generate propulsion (no braking) as soon as the poles make contact with the ground. Altogether, no conclusive evidence for or against the occurrence of stretch-shortening cycle activity in upper-extremity extensors were provided. The different results between the different modes of DP and the fact that other mechanisms (power transfer) than stretch-shortening may prevail in explaining the observed upper-extremity movement and dynamics patterns in DP means that future studies are warranted to examine these issues further. Studies exclusively dealing with such an issue, combining muscle activity measurements with kinematics and dynamics, estimating length changes of muscle contractile elements and series elastic elements may further our understanding of the neuromuscular control mechanisms involved in DP.

Possible stretch-shortening mechanisms in upper-extremity extensor muscle-tendons have received much attention. Although flexion-extension movement characteristics are evident also in the lower extremity and trunk, especially in hip and knee joints, no studies have explicitly discussed possible stretch-shortening mechanisms in lower-extremity muscle-tendons. For the lower extremity, a reversal of motion of CoM is present, and the joints produce and absorb power continuously throughout both the poling and swing phase. Throughout this thesis, negative lower-extremity power was immediately followed by positive power, coinciding with flexion and extension movements, with the change from flexion to extension coinciding with the more or less rapid change from body lowering to heightening towards the end of the poling phase. These patterns generally remained very similar at all intensities and conditions studied in this thesis and, altogether, point to the occurrence of stretch-shortening of lower-extremity and trunk extensors during the change from body lowering to heightening. Though only partly studied here, the change from body lowering to heightening generally seem to become even more abrupt at very high speeds, e.g., during the final spurt. Thus, the perpendicular body movements thereby becomes more bouncing-like. The role of any stretch-

shortening behaviour of lower-extremity and trunk extensors may most likely be linked to reutilization of the excessive body energy that is absorbed during the poling phase, especially on the level and at slight inclines and at the highest speeds. If this excessive energy is not reutilised, it would be wasted. Lower-extremity and trunk stretch-shortening may also be related to potentiation of muscle force production, or to what was discussed for the upper-extremity extensors, more work can be done due to higher muscle force levels at the beginning of body heightening (e.g., Bobbert et al., 2006; 1996).

From the joint-specific powers in study I, very little positive knee power was found, and it was mentioned in that study that little knee work is associated with body heightening and repositioning. It should be mentioned, however, that the small flexor knee moment during most of knee extension (body heightening) may reflect that power is transferred from the knee extensors to the ankle via the bi-articular gastrocnemius muscle (Bobbert & van Ingen Schenau, 1988; van Soest et al., 1993). In general, findings of minimal joint power magnitudes does not necessarily mean that muscles surrounding that joint is not of importance for optimising movement. Likewise, large amount of power about a specific joint does not necessarily mean that this power is directly associated with muscles surrounding the specific joint. Power that computationally shows up as for example shoulder power may reflect power transferred from the elbow via bi-articular parts of e.g., triceps brachii or biceps brachii. To get a deeper understanding of these issues in the DP movement, dynamics analysis should be combined with electromyography and estimations of mono- and bi-articular muscle-tendon length changes.

Methodological considerations

In assessment of kinematic data, high-frequency noise is often a problem that needs to be taken care of by low-pass filtering (Pezzack et al., 1977; Winter et al., 1974). High-frequency noise were more apparent in level treadmill DP (study I) and thus lower cut-off frequencies were needed. However, noise is still present and likely affected kinematic measurements more in the level DP situation than in uphill. This is mostly due to higher movement speeds, especially of the markers attached to the poles and arms, which during the abrupt pole-to-ground collision cause marker-and-skin vibrations. This was especially apparent at the highest speed (27 km/h). Ideally, future studies should perform the same line of investigations, but include measurements of force (including ski forces). Estimations of body mechanical energy based on force may generally be of higher accuracy by containing less noise, and the noise present is less of an issue in integration than in obtaining the first or second derivative. It should be noted, however, that such an analysis would not include rotational kinetic energy, which still need to be based on

kinematic analysis. Although less of an issue in DP – a symmetrical and synchronous movement (i.e., left and right arm and leg moves in the same direction at all times) – in DIA, the left arm is moved forward while the right arm is moved backwards. These type of movements may contain significant energy changes which may be completely cancelled in force based CoM energy analysis (Winter, 1979; Zatsiorsky, 1998).

In terms of joint moment (and power) analysis, one faces the problem of obtaining reliable moment data about the trunk segment, especially in DP. Thus, the current studies can merely speculate about trunk contribution, and some of the trunk power obtained in this thesis may belong to shoulder or hip contributions. In DIA, the trunk is kept more stable, and may more validly be considered as one rigid segment in modelling.

Future lines of investigation

As mentioned this thesis did not analyse full-spurt DP, which often is the main differentiating condition between the very top placed skiers (e.g. 1st – 3rd) and those placed lower on the result list, e.g., outside of the podium. The main goal of this thesis was to provide a more general understanding of the underlying fundamental principles of DP dynamics and energetics, and less to investigate differences between the very top-placed skiers versus those of slightly lower (spurt) performance levels. However, such investigation may provide useful insight into coordination and timing of dynamics that may be important in the process of optimising technical and physiological aspects of both submaximal and maximal DP for both elite and sub-elite skiers.

The skiers participating in this study were generally ranked as (Norwegian) national class skiers. That is, their performance level is of high standard. However, only a few can be considered top world class skiers, that is, skiers that regularly participate and win medals in the World Cup, World Championships or the Olympics. Also, all skiers are typical all-round skiers or performing best in sprint competitions. None of the skiers were involved in Marathon skiing (Ski Classics). In the later years, a larger number of skiers are training full-time solely to compete in long Ski Classics races, and a large number of these skiers choose DP exclusively in almost all ski-specific (on-snow or roller skiing) training and racing. Such skiers may be considered the very top experts in DP, although such skiers normally are not trained to perform extremely well in sprint-like DP (>30 km/h), but rather to double-pole at medium-to-high speeds for prolonged times (~18-25 km/h for 3-5 hours in e.g. Vasaloppet). It would be of interest to compare different ‘specialists’ who rely on DP in different ways (sprint, Marathon

racers, all-round) as well as skiers of more distinctly different performance levels to elucidate the details of importance.

Several studies have shown that there is an increasing gender difference in the ability to generate power output the higher the involvement of the upper body (Hegge et al., 2016; Sandbakk et al., 2012; Sandbakk et al., 2018). In addition, these gender differences increase further when the exercise intensity increases (Hegge et al., 2015). Since this thesis only included males, future studies should investigate whether such gender differences are due to technical and dynamic aspects as well, though these may be in part due to the differences in physiological capacities (Hegge et al., 2016).

In other cyclic sports such as e.g., cycling, it has been shown that cycle rate (or cadence) has a direct effect on coordination and joint-specific power contributions to total power output (McDaniel et al., 2014; Skovereng et al., 2016). Any possible relationship between cycle rate and joint power contributions in DP were not examined in this thesis. Lindinger and Holmberg (2011) found that manipulating cycle rate in DP affected pole force generation, kinematics and the physiological response and these issues are likely linked to differences in joint dynamics and joint power contributions. In DP and in other XC-skiing sub-techniques, the better skiers seem to ski with lower cycle rates and longer cycle lengths at a given speed as well as with longer cycle lengths at higher absolute speeds (Sandbakk & Holmberg, 2014; Sandbakk et al., 2010). Whether such findings are related to simply more joint power or a redistribution in the relative joint power contributions needs to be examined in future studies.

Conclusions

The primary aim of this thesis was to examine the energetics and dynamics of the DP sub-technique in classical style cross-country skiing, in particular with regard to the specific sources of generation and destination of mechanical energy in different DP conditions (ergometer DP and both level and uphill roller-skiing DP). Both whole-body and joint dynamics were studied. The effect of exercise intensity, speed and incline-speed combinations on body movements and related mechanical energy changes, and upper-extremity and lower-extremity and trunk contribution to total power output, was examined.

In DP, propulsive forces are provided solely through the poles and therefore upper-extremity power contribution to total power output is accentuated. Study **I** found that, in ergometer DP, the upper-extremity power contribution was 51% during low-intensity DP and 33% during maximal-intensity DP. Accordingly, the lower extremity and trunk is an increasingly large source of energy generation in ergometer DP. Study **II** found that, in roller-skiing DP on the level, the upper-extremity power contribution was 63% at low speed ($15 \text{ km}\cdot\text{h}^{-1}$) and 66% at moderate ($21 \text{ km}\cdot\text{h}^{-1}$) and high ($27 \text{ km}\cdot\text{h}^{-1}$) speeds. Study **III** found that, in uphill roller-skiing DP, the upper-extremity power contribution was 63% at slight incline (5% incline) and 54% at steep incline (12% incline), but unaffected by work rate (i.e., speed at each incline).

The way in which the lower extremity can contribute to power output, which in DP is finally delivered through the poles, is by doing considerable work during the swing phase. During the swing phase, the body is repositioned and heightened while the poles are brought forward to the next point of contact. During the following poling phase, the body is rapidly lowered and the amount of force applied to the poles can, by effective use of body mass, be increased. Work done by the lower extremity during the swing phase is temporarily 'stored' as body (potential) mechanical energy. During the poling phase, part of this energy is transferred to pole propulsion power. This technique requires (an exhaustive) repetitive heightening and lowering of the body, which becomes more pronounced with increasing intensity or speed. These aspects were essentially similar in all DP conditions studied here.

Differences in upper- and lower-extremity dynamics were found between ergometer and roller skiing DP. These differences are likely due to available horizontal friction forces on the full friction floor surface in ergometer DP, which can be used to appropriately direct the ground reaction force variably. During the poling phase, the poling force generates backward rotation of the body about the CoM. This rotation must be balanced by a ground reaction force acting

behind the CoM, generating a forward rotating moment. In roller skiing or on-snow skiing DP the way to handle this dynamic constraint will be different, since the direction of the ski reaction force will be dictated mainly by the normal force. This mechanical difference requires differences in coordination and therefore joint dynamics (moment) and energetics (power) and likely explains the (large) effect of intensity on upper- and lower-extremity power contribution found in ergometer DP but not in roller-skiing DP.

In all DP conditions studied here, but especially in level roller-skiing DP, the lower extremity absorbs some of the decreasing body mechanical energy during the poling phase, i.e., energy that is not directly used for propulsion. This may be energetically ineffective. However, part of the energy absorbed by the lower extremity may be stored and reutilised in stretch-shortening of muscle-tendons during the bouncing-like transition from body lowering to heightening. Moreover, another explanation might be that lower-extremity power generation for propulsion purposes is only part of the reason for the exhaustive heightening-lowering of the body. Another reason may be that it is the only way to position the body and poles in a position/condition by which the upper extremity can generate large amounts of power in a rather short time period, at low effort. The amount of lower-extremity energy absorption was least at steep incline, where also less power is generated by the upper extremity during a longer poling time than at slight incline or level DP. Interestingly, skiers perceive this lower upper-extremity power generation at steep incline as more demanding. This is likely related to a disadvantageous working condition, i.e., altered body and pole positioning related to incline effects on gravity-surface relation at the steep incline.

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Paper I



Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers



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ARTICLE INFO

Keywords:

Dynamic constraints
Power
Mechanical energy
Force
Cross-country skiing

ABSTRACT

The purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in ergometer double poling (DP), while taking specific dynamic constraints into account. One main question was whether lower-body power contribution increased or decreased with increasing intensity. Nine male Norwegian national-level cross-country skiers performed ergometer DP at low, moderate, high and maximal intensity. Kinematics, and ground (GRF) and poling (F_{poling}) reaction forces were recorded and used in link segment modeling to obtain joint and whole-body dynamics. Joint powers were averaged over the cycle, the poling (PP) and recovery (RP) phases. The contribution of these average powers was their ratios to cycle average poling power. At all intensities, the shoulder (in PP) and hip (mostly in RP) generated most power. Averaged over the cycle, lower-body contribution (sum of ankle, knee and hip power) increased from ~37% at low to ~54% at maximal intensity ($p < .001$), originating mostly from increased hip contribution within PP, not RP. The generation of larger F_{poling} at higher intensities demanded a reversal of hip and knee moment. This was necessary to appropriately direct the GRF vector as required to balance the moment about center of mass generated by F_{poling} (control of angular momentum). This was reflected in that the hip changed from mostly absorbing to generating power in PP at lower and higher intensities, respectively. Our data indicate that power-transfer rather than stretch-shortening mechanisms may occur in/between the shoulder and elbow during PP. For the lower extremities, stretch-shortening mechanisms may occur in hip, knee and trunk extensors, ensuring energy conservation or force potentiation during the countermovement-like transition from body lowering to heightening. In DP locomotion, increasing intensity and power output is achieved by increased lower-body contribution. This is, at least in ergometer DP, partly due to changes in joint dynamics in how to handle dynamic constraints at different intensities.

1. Introduction

In most cross-country (XC) skiing techniques, forward motion is made possible by generation of propulsive forces applied to the ground by the skier through the poles and skis. As such, transformation of power generated by muscle to external power and speed relies on coordinated interaction between the joints and segments of both the upper and lower body (e.g., Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005; Lindinger, Holmberg, Müller, & Rapp, 2009; Lindinger, Stöggl, Müller, & Holmberg, 2009). Double

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<https://doi.org/10.1016/j.humov.2017.11.010>

Received 5 September 2017; Received in revised form 3 November 2017; Accepted 18 November 2017

Available online 24 November 2017

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poling (DP), one of the main classical style XC skiing techniques, is the only technique in which propulsive forces are applied solely through the poles. This is because in DP the skis continuously glide, whereby only motion-resisting friction forces occur between skis and surface and it is not possible to produce thrust in the forward direction. The same principle applies to DP on an ergometer (e.g., the Concept2 SkiErg frequently used in XC ski training): although the athlete stands on a full friction surface (ground), external poling power (P_{poling}) is finally produced through a set of ropes resisted by an external device (see e.g., Danielsen, Sandbakk, Holmberg, & Ettema, 2015). Therefore, upper body work is accentuated in DP (e.g., Dahl, Sandbakk, Danielsen, & Ettema, 2017; Danielsen et al., 2015; Holmberg et al., 2005). Still, via a transfer of body mechanical energy (E_{body}), P_{poling} can to a large extent originate from energy generated by lower body muscles (see Danielsen et al., 2015).

We previously showed that, in ergometer DP, work done by the extending lower body is mainly done in the recovery phase (RP), which increases E_{body} (Danielsen et al., 2015). As the center of mass (CoM) is lowered and the body rotated forward in the following poling phase (PP), part of this E_{body} is transferred to external ergometer work (i.e., one ‘falls’ on the ropes). It was estimated that ~66% and ~53% of net muscle work over the movement cycle was done in the RP at low and maximal intensity, respectively, presumably by lower body muscles. Accordingly, the remainder should originate from upper body work, which directly leads to P_{poling} .

The estimation that more than 50% of net muscle work was done by the lower body was based on the assumption that the PP and RP separate work done by the upper and lower body, respectively. However, this amount did not increase but rather decreased when intensity increased, which is in disagreement with e.g., Bojsen-Møller et al. (2010), Rud, Secher, Nilsson, Smith, and Hallén (2014) and Zoppirolli et al. (2016). They found that increasing both ergometer and skiing DP intensity relied more upon increased lower than upper body involvement. Of course, the assumption made in the previous investigation (Danielsen et al., 2015) might not be correct; the amount of work done by the upper and lower body does not necessarily correspond to the poling-recovery division. For example, repositioning of the body through trunk, hip, and knee extension start slightly before the end of PP (Danielsen et al., 2015; Holmberg et al., 2005).

In Danielsen et al. (2015) it was also assumed that most of the decreasing E_{body} during PP was used directly for propulsion. However, at the start of PP a small but significant part was absorbed by muscles, most likely in the lower extremity. This raised the question of whether lower body muscle-tendons store and reutilize mechanical energy in stretch-shortening cycles (SSC) in the countermovement-like action that is the immediate transition from body lowering to heightening. An inverse dynamics analysis is needed to elucidate these issues.

An analysis of dynamics may also shed light on an often overlooked issue in DP, which is the need to control changes in body angular momentum by appropriately balancing the net moment about the CoM. The generation of oblique poling forces (F_{poling}) poses specific requirements on the moment about CoM generated by the ground reaction force (GRF) of the lower extremity, which must counteract the moment generated by F_{poling} . This dynamic constraint demands specific joint moments and powers generated by appropriate coordination, which may be affected by intensity.

Accordingly, the main purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in ergometer DP. In particular, we re-examined the relationship between lower-body power contribution and DP intensity. We hypothesized that, given our earlier findings (Danielsen et al., 2015), in case the relationship is positive it should coincide with considerable work done by the lower body during PP. Moreover, taking specific dynamic constraints into account, we aimed to further our understanding of DP energetics and dynamics with regard to joint power generation, absorption and possible transfer.

2. Methods

The experimental procedures and data of the present paper originate partly from a previous study (Danielsen et al., 2015), where the main purpose was to examine fluctuations in body mechanical energy in relation to external ergometer work as well as to estimate instantaneous net muscle-tendon work rate.

2.1. Participants

Nine male Norwegian national level XC skiers (age 24 ± 5 yrs, height 1.86 ± 0.06 m, body mass 81.7 ± 6.5 kg, $VO_{2\text{peak}}$ running 73 ± 6 ml·kg⁻¹·min⁻¹) voluntarily participated in this study. Before providing written informed consent, the participants were verbally informed about the nature of the study and their right to withdraw at any point was explicitly stated. Permission to conduct the study was given by the Regional Committee for Medical and Health Research Ethics in Central Norway, and the study was registered at Norwegian Science Data Services.

2.2. Experimental design

Following a 15-min warm-up of low intensity running on a treadmill and ergometer DP, the participants performed three 4-min submaximal trials of DP at low (LOW), moderate (MOD), and high (HIGH) intensity levels, with 1–2 min rest between the trials. After an active recovery period of ~5 min the participants completed one 3-min closed-end performance test (MAX). During each trial, kinetics and kinematics were collected after steady-state external power production had been achieved.

DP was performed on a Concept2 SkiErg (Concept2 Inc., Morrisville, VT, USA) mounted to the wall. The aero-resistance of the ergometer was set at the lowest level to minimize poling times, thereby best mimicking skiing DP (Halonen et al., 2015). The advantage of using ergometer DP as a model is that the definition of instantaneous external power is unambiguous (as opposed to ski

DP) and measurement of external forces is extremely accurate.

All trials were performed with the participants standing on a force plate secured on the floor, wearing running shoes. In order to ensure that the participants maintained the same position in front of the ergometer, a steel plate was secured on the force plate in front of the feet at a distance from the ergometer that most closely simulated DP movements on snow or roller skiing (Halonen et al., 2015). All skiers were familiarized with DP on the ergometer, which was frequently used in their normal training routines.

For inter-individual comparisons, the skiers were instructed to perform the trials at rating of perceived exertion (RPE) values of ~10, ~13, ~16 and 20 at LOW, MOD, HIGH and MAX, respectively, on the Borg 6–20 scale (Borg, 1970). Accordingly, the participants generated external power outputs in relation to their own performance levels and body size. All participants had at least 6 yr experience in performing extensive endurance training and were considered experienced in subjective control of intensity. The integrated SkiErg performance monitor (PM4) displayed the mean DP power output delivered to the ergometer, allowing each subject to monitor and maintain the power output as stable as possible throughout the submaximal trials as instructed. MAX was performed at maximal sustainable effort, although the participants spent the initial ~10–20 s to attain a power production they deemed sustainable for 3 min. The participants performed all trials at their own freely chosen cycle rates.

2.3. Kinetic and kinematic measurements

Poling force (F_{poling}) was measured using a Futek Miniature Tension and Compression Load Cell (Futek LCM200, capacity 250 lb, non-linearity $\pm 0.5\%$, hysteresis $\pm 0.5\%$, weight 17 g, Futek Inc., Irvine, CA, USA) which was mounted in series with the drive cord inside the casing of the ergometer using a Rod End Bearing (Futek, GOD00730). The load cell was calibrated against a range of forces of known magnitude employing calibrated weights. GRF was measured by a Kistler force plate (Kistler 9286BA, Kistler Instrumente AG, Winterthur, Switzerland). All force data were sampled at 500 Hz.

Seven infrared Oqus cameras (Qualisys AB, Gothenburg, Sweden) captured three-dimensional position characteristics of passive, spherical reflective markers at a sampling frequency of 100 Hz. Four markers were fixed on the ergometer to measure the poling movement: two on the right and left handles and two on the right and left points where the ropes entered the ergometer. Two reference markers were placed on the force plate in order to describe the point of application of the GRF within the global coordinate system. Seven reflective markers were placed on the left side of the body (using double-sided tape; 3 M, Maplewood, MN, USA) at the following anatomical landmarks: distal end of the fifth metatarsal (on the shoe), lateral malleolus, lateral femoral epicondyle, trochanter major, lateral end of the acromion process, lateral humeral epicondyle and ulnar styloid process. All force and movement data were recorded simultaneously and synchronized using the Qualisys Track Manager software (Qualisys AB). Offline data processing was done in MATLAB 8.1.0. (R2013a, Mathworks Inc., Natick, MA, USA).

2.4. Data analysis

Force and kinematic data were low-pass filtered (8th order, zero-lag Butterworth filter) cutting off at 50 and 25 Hz, respectively. Because there are no typical impact forces in the present setup, the use of different cut-offs for kinematics and kinetics had no impact on joint moment calculations as visually checked (e.g., van den Bogert & de Koning, 1996). Bilateral movement symmetry was assumed, so the position data of the left side of the body was assumed to be the average of left and right, and all data were analyzed in the sagittal plane. The sagittal plane limb segments were defined as foot, leg, thigh, trunk (including head), arm, and forearm (see Fig. 1). Segment lengths were determined from marker coordinates and averaged over the entire period of analysis. Masses, moments of inertia, and center of mass of the segments were calculated using the anthropometric data according to de Leva (1996) and individual body mass and segment lengths. Linear and angular velocities and accelerations of the limb segments and the velocity of the poling handles relative to the ergometer were calculated by numerical differentiation of position data with respect to time. Instantaneous net joint moments were obtained using inverse dynamics by solving the equations of motion for a linked segment model (Elftman, 1939). For the ankle moment the GRF was the external force, while for the elbow moment F_{poling} was the external force (Fig. 1). Extending joint moments and velocities (including plantar flexion) were defined positive. Joint power was calculated by multiplication of net joint moment and joint angular velocity.

Instantaneous P_{poling} was calculated as F_{poling} multiplied by the poling handle velocity. In DP locomotion considerable flexion and extension movements occur in the non-rigid trunk segment not modelled here, likely involving power. Due to the inherent problem in obtaining reliable net moment data about the non-rigid trunk, we used a rationale similar to e.g., Riddick and Kuo (2016) to account for power associated with trunk movements. According to the instantaneous power equation of van Ingen Schenau and Cavanagh (1990), at each instant in time, the sum of joint powers (P_j , the power source), derived from rigid body inverse dynamics, must equal the sum of the two possible power destinations; the time rate of change of E_{body} (\dot{E}_{body}) and the power that flows to the external environment (P_{poling}):

$$\sum_{j=1}^5 P_j = \dot{E}_{\text{body}} + P_{\text{poling}} \quad (1)$$

where P_j is the power at joint j . However, because within-trunk movements were neglected in the inverse dynamics, any difference between P_j and $\dot{E}_{\text{body}} + P_{\text{poling}}$ was accounted for as trunk power:

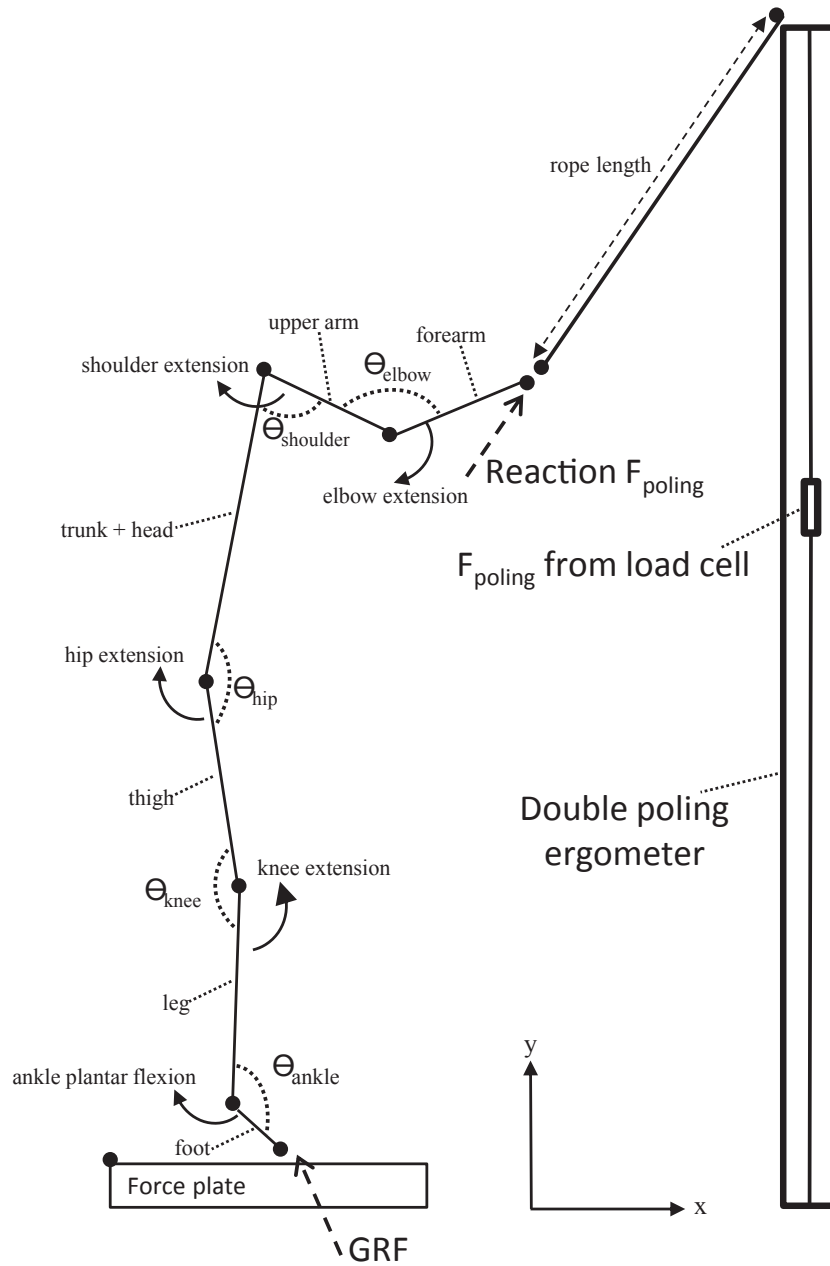


Fig. 1. Illustration of marker placements (black dots), segments, definition of joint angles, and external forces.

$$P_{\text{trunk}} = (\dot{E}_{\text{body}} + P_{\text{poling}}) - \sum_{j=1}^5 P_j \tag{2}$$

\dot{E}_{body} is:

$$\dot{E}_{\text{body}} = \frac{dE_{\text{body}}}{dt} \tag{3}$$

E_{body} is the total body energy, calculated by summation across all 6 segments:

$$E_{\text{body}} = \sum_{i=1}^6 E_i \quad (4)$$

where E_i is the total energy of segment i :

$$E_i = \frac{1}{2}m_i v_i^2 + m_i g h_i + \frac{1}{2}I_i \omega_i^2 \quad (5)$$

where m_i is segment mass (kg), v_i is segment absolute velocity ($\text{m}\cdot\text{s}^{-1}$), g is gravitational acceleration ($9.81 \text{ m}\cdot\text{s}^{-2}$), h_i is segment height above ground (m), I_i is segment moment of inertia ($\text{kg}\cdot\text{m}^2$), and ω_i is segment angular velocity ($\text{rad}\cdot\text{s}^{-1}$).

With the feet remaining on the ground at all times, and with only a simple set of pulleys between the load cell and movement registration, we assumed that power associated with friction was negligible. Finally, the moment generated about CoM by the reaction force of F_{poling} and the GRF, as well as their sum (net moment about CoM), was calculated.

One DP cycle was defined as from the shortest to the subsequent shortest length of the ropes. The poling phase was defined as from the shortest to the longest length of the ropes, and the recovery phase was defined as from the longest to the shortest length of the ropes. Poling time (PT) was defined as the duration of the poling phase, cycle time (CT) as the duration of an entire poling + recovery movement, relative PT as the percentage of CT, and cycle rate (CR) as the number of poling cycles per second.

All data, including joint powers (elbow, shoulder, hip, knee, ankle, and trunk), were time normalized and averaged over ~ 20 cycles for each subject at each of the intensities, and then averaged across subjects. Joint powers were averaged over the cycle, the PP, and the RP, separately for each participant. Relative joint power values were then calculated as the ratio of these average joint power values to cycle average P_{poling} ($P_{\text{poling-mean}}$).

2.5. Statistical analysis

All data were checked for normality by visual inspection of normal Q-Q plots and histograms and are presented as means \pm 95% CI. To determine the effect of intensity, one-way analysis of variance (ANOVA) with repeated measures for intensity was performed on each dependent variable (absolute and relative joint powers (averaged over the cycle, the PP and the RP), $P_{\text{poling-mean}}$, CR, absolute and relative PT, and relevant kinematic variables). For $P_{\text{poling-mean}}$, the difference contrasts were tested for significance to confirm that the protocol induced four different work intensities. Similarly, for RPE (reported as median \pm IQR), a Wilcoxon rank tests was used to test for differences between adjacent intensities. Statistical significance was based on $\alpha = 0.05$ and all statistical tests were performed using SPSS version 24 (IBM Inc., Armonk, NY, USA).

3. Results

3.1. Basic cycle characteristics

All reported RPE values were close to target values (9 ± 3 , 13 ± 1 , 15 ± 2 , 19 ± 0), and were significantly different between adjacent intensities ($p < .01$). Ergometer DP at these intensities corresponded to $P_{\text{poling-mean}}$ of 116 ± 10 , 166 ± 22 , 214 ± 25 , and 306 ± 25 W, which were significantly different between adjacent intensities ($p < .001$). Note that the increase in $P_{\text{poling-mean}}$ was ~ 50 W between submaximal intensities and ~ 90 W between HIGH and MAX. CR increased (0.74 ± 0.06 , 0.78 ± 0.06 , 0.84 ± 0.07 , and $0.97 \pm 0.07 \text{ s}^{-1}$) and PT decreased (0.62 ± 0.04 , 0.58 ± 0.03 , 0.54 ± 0.03 , and 0.49 ± 0.02 s) with intensity ($p < .05$), while relative PT remained similar from LOW to HIGH ($\sim 45 \pm 1\%$) and slightly increased from HIGH to MAX ($\sim 47 \pm 1\%$; $p < .05$).

3.2. Forces and kinematics

Across all intensities, F_{poling} as well as GRF showed very similar patterns (Fig. 2A–C). In Fig. 2D and E a stick figure of one representative skier, including dynamics, is shown at LOW and MAX. In general, the gross movement pattern remained similar across all intensities, while the magnitude of forces and ranges of motion increased ($p < .05$; Fig. 3A–J). Increasing intensity led to an increased within-cycle vertical fluctuation of CoM (Fig. 2D and E; $p < .001$). Note that the minimum CoM height decreased more with intensity (~ 10 cm from LOW to MAX) than the maximum height increased (~ 3 cm from LOW to MAX). This pattern is reflected in hip – and knee joint angle range of motion (Fig. 3C, D). The shoulder mostly extended throughout the PP, while the elbow showed a distinct flexion-extension movement pattern (Fig. 3A, B). Since CR increased, almost all joint (mean flexion and extension) angular velocities increased with intensity ($p < .05$; Fig. 3F–J).

3.3. Moments and powers

The moment about CoM caused by F_{poling} and the GRF are shown in Fig. 2F. During poling, the reaction force of F_{poling} tended to rotate the body backwards (i.e., acting in front of the CoM). This was opposed by a generally forward rotating effect of GRF (i.e., acting behind the CoM).

Across intensities, the net joint moments progressively increased (Fig. 3K–O). Similarly, joint powers showed comparable patterns across all intensities, though progressively increasing in magnitude (Fig. 3P–T) with one exception: at LOW and MOD a hip extensor

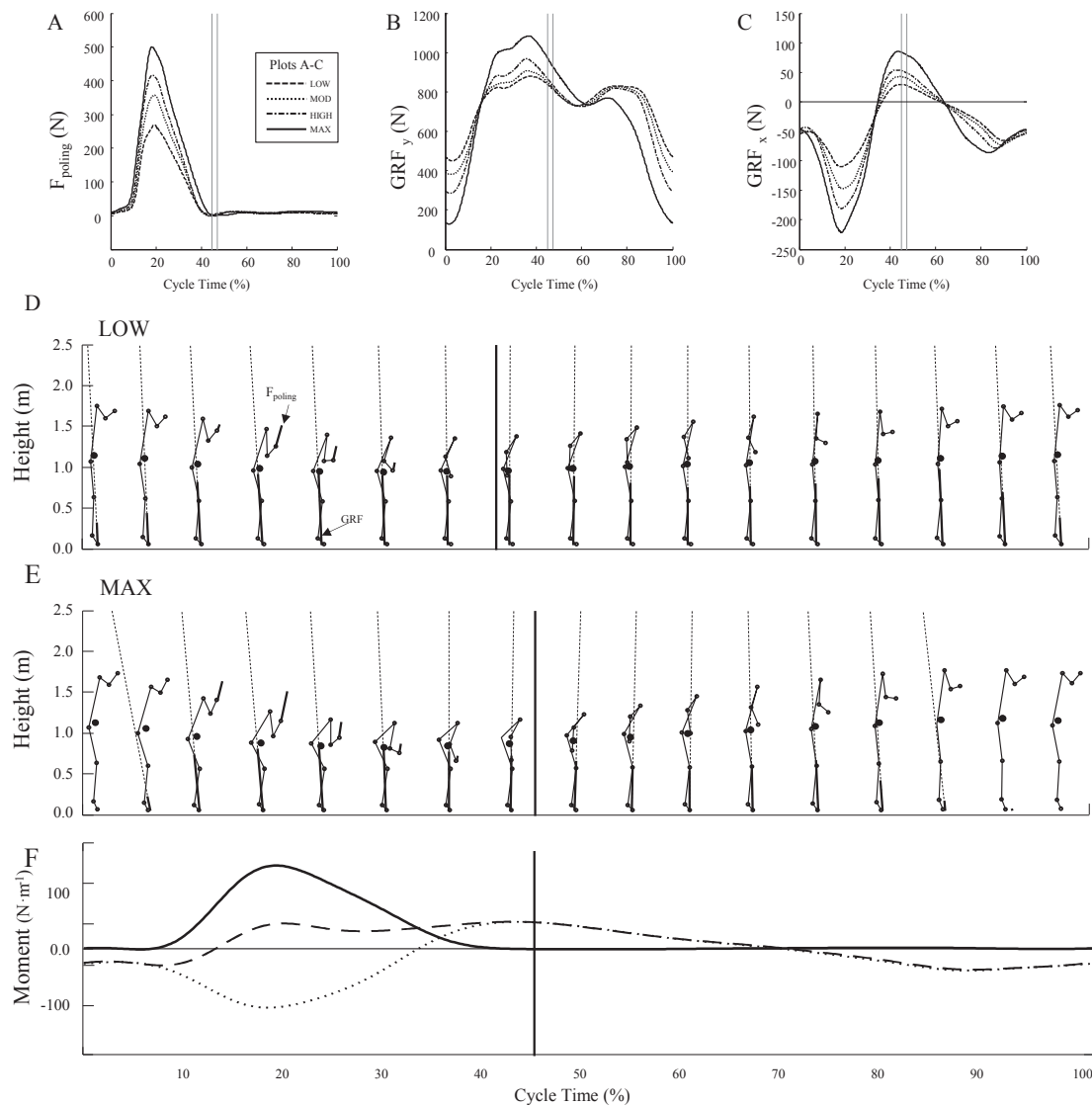


Fig. 2. A Time trajectories of poling force (F_{poling}), B the vertical component of ground reaction force (GRF_y), and C the horizontal component of GRF (GRF_x). Values are the means over all subjects ($N = 9$). The vertical lines represent end of poling phase. D and E Stickfigure of a typical example shown at different time points during an ergometer double poling cycle at intensities LOW (D) and MAX (E). The reconstruction of the GRF, the poling force (F_{poling}) and the CoM (black circle) are shown. The dashed GRF lines represent a magnification of the true GRF (solid black lines) to better illustrate its line of action. F Moment about CoM caused by reaction F_{poling} (solid line), the GRF (dotted line), and the net moment (dashed line), at intensity HIGH, mean of all subjects.

moment occurred throughout the movement cycle, which changed into a flexor moment in the recovery-to-poling transition period at HIGH and especially MAX (Fig. 3M). This is reflected in substantial positive hip power in the same time period (Fig. 3R). Furthermore, the high peak extending moment and corresponding peak power at the hip in MAX in the poling-to-recovery transition period are the clearest effects in accordance with the large power difference (~ 90 W) between HIGH and MAX.

Averaged absolute and relative joint powers are shown in Table 1. Over the entire cycle, most power was produced at the hip and shoulder at all intensities. Power at ankle, hip, shoulder and trunk increased ($p < .001$) while elbow power decreased ($p < .05$) with increasing intensity (Table 1). Relative hip power increased while relative shoulder power decreased ($p < .001$). The contributions from ankle and elbow were rather small but still somewhat affected by intensity. Trunk contribution remained similar at $\sim 13\%$. Lower body power (sum of ankle, knee and hip) amounted to $\sim 37 \pm 5\%$, $\sim 39 \pm 5\%$, $\sim 43 \pm 4\%$ and $\sim 54 \pm 5\%$ at LOW, MOD, HIGH and MAX, respectively. That is, the relative contribution from the lower body substantially increased with

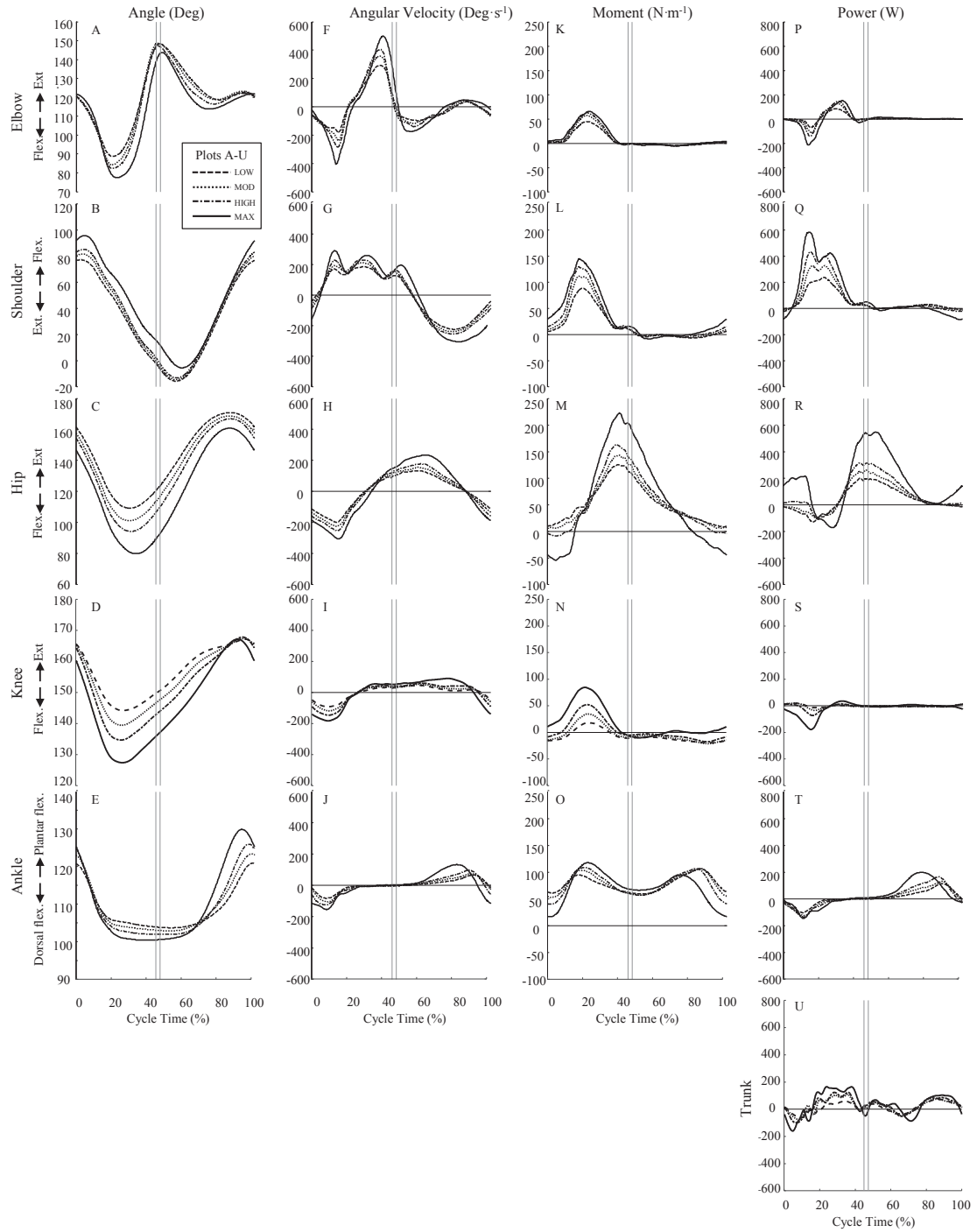


Fig. 3. Mean curves of joint angles (A–E), joint angular velocities (F–J), net joint moments (K–O) and joint powers (P–U) plotted against normalized cycle time at the 4 intensities while ergometer double poling (N = 9). The vertical lines indicate end of poling phase at submaximal (left) and maximal (right) intensities.

Table 1

Absolute (W) and relative (%) joint power (mean ± 95% confidence interval, N = 9) while ergometer double poling at increasing intensities. A Joint power averaged over the cycle and their contribution to cycle average poling power ($P_{\text{poling-mean}}$). B Joint power averaged over the poling phase and their contribution to $P_{\text{poling-mean}}$. C Joint power averaged over the recovery phase and their contribution to $P_{\text{poling-mean}}$.

Intensity	Ankle	Knee	Hip	Shoulder	Elbow	Trunk
A Cycle						
LOW	6 ± 3 W	-2 ± 3 W	38 ± 7 W	52 ± 10 W	6 ± 6 W	15 ± 6 W
MOD	9 ± 4 W	-3 ± 4 W	58 ± 7 W	69 ± 13 W	8 ± 9 W	25 ± 12 W
HIGH	13 ± 6 W	-7 ± 4 W	84 ± 10 W	85 ± 17 W	7 ± 9 W	31 ± 10 W
MAX	22 ± 7 W	-20 ± 7 W	164 ± 16 W	104 ± 21 W	-1 ± 13 W	39 ± 12 W
	$F_{3,24} = 25, p < .001$	$F_{3,24} = 63, p < .001$	$F_{3,24} = 219, p < .001$	$F_{3,27} = 42, p < .001$	$F_{3,24} = 3.9, p = .020$	$F_{3,24} = 16, p = .001$
LOW	5 ± 2%	-2 ± 3%	33 ± 7%	45 ± 6%	6 ± 5%	13 ± 6%
MOD	5 ± 3%	-2 ± 2%	37 ± 8%	42 ± 6%	5 ± 5%	14 ± 6%
HIGH	6 ± 3%	-3 ± 2%	40 ± 5%	40 ± 6%	3 ± 4%	14 ± 5%
MAX	7 ± 2%	-7 ± 2%	54 ± 6%	33 ± 5%	0 ± 4%	12 ± 4%
	$F_{3,24} = 3.9, p = .022$	$F_{3,24} = 50, p < .001$	$F_{3,24} = 57, p < .001$	$F_{3,27} = 19, p < .001$	$F_{3,24} = 12, p < .001$	$F_{3,24} = 0.4, p = .769$
B Poling phase						
LOW	-33 ± 11 W	0 ± 4 W	0 ± 14 W	104 ± 20 W	12 ± 12 W	5 ± 13 W
MOD	-41 ± 13 W	-3 ± 3 W	19 ± 14 W	145 ± 30 W	16 ± 19 W	28 ± 26 W
HIGH	-46 ± 14 W	-11 ± 4 W	47 ± 18 W	185 ± 37 W	14 ± 21 W	29 ± 16 W
MAX	-45 ± 13 W	-40 ± 7 W	123 ± 26 W	232 ± 47 W	-7 ± 28 W	45 ± 26 W
	$F_{3,24} = 4.5, p = .014$	$F_{3,24} = 147, p < .001$	$F_{3,24} = 96, p < .001$	$F_{3,27} = 55, p < .001$	$F_{3,24} = 5.4, p = .006$	$F_{3,24} = 6.5, p < .01$
LOW	-28 ± 8%	0 ± 4%	0 ± 12%	88 ± 10%	11 ± 10%	5 ± 12%
MOD	-24 ± 8%	-2 ± 2%	11 ± 7%	87 ± 12%	10 ± 11%	15 ± 14%
HIGH	-21 ± 5%	-5 ± 2%	21 ± 7%	85 ± 11%	7 ± 10%	13 ± 8%
MAX	-14 ± 4%	-13 ± 2%	41 ± 8%	75 ± 11%	-2 ± 9%	14 ± 9%
	$F_{3,24} = 9.2, p < .001$	$F_{3,24} = 69, p < .001$	$F_{3,24} = 48, p < .001$	$F_{3,27} = 16, p < .001$	$F_{3,24} = 14, p < .001$	$F_{3,24} = 2.8, p = .090$
C Recovery phase						
LOW	39 ± 15 W	-4 ± 4 W	71 ± 17 W	10 ± 6 W	1 ± 1 W	24 ± 8 W
MOD	50 ± 19 W	-4 ± 5 W	90 ± 17 W	7 ± 7 W	2 ± 1 W	23 ± 13 W
HIGH	62 ± 22 W	-3 ± 7 W	116 ± 20 W	3 ± 8 W	2 ± 1 W	33 ± 15 W
MAX	83 ± 19 W	-3 ± 7 W	200 ± 35 W	-13 ± 9 W	4 ± 1 W	34 ± 18 W
	$F_{3,24} = 37, p < .001$	$F_{3,24} = 0.2, p = .888$	$F_{3,24} = 73, p < .001$	$F_{3,27} = 16, p < .001$	$F_{3,24} = 6.0, p = .003$	$F_{3,24} = 1.3, p = .293$
LOW	33 ± 11%	-3 ± 3%	62 ± 16%	8 ± 5%	1 ± 1%	20 ± 6%
MOD	29 ± 11%	-3 ± 3%	58 ± 17%	5 ± 4%	1 ± 1%	13 ± 6%
HIGH	28 ± 9%	-2 ± 3%	56 ± 12%	2 ± 4%	1 ± 1%	15 ± 6%
MAX	27 ± 5%	-1 ± 2%	66 ± 12%	-4 ± 3%	1 ± 0%	11 ± 6%
	$F_{3,24} = 1.5, p = .252$	$F_{3,24} = 3.5, p = .030$	$F_{3,24} = 2.5, p = .084$	$F_{3,27} = 16, p < .001$	$F_{3,24} = 0.8, p = .509$	$F_{3,24} = 2.8, p = .100$

intensity ($p < .001$).

During PP, the shoulder generated considerable power at all intensities (Table 1). Shoulder power rapidly increased to a (large) peak, coinciding with peak F_{poling} as well as with the peak in negative elbow power (Fig. 3P, Q). Elbow, trunk, and hip power were both positive and negative (Fig. 3P, R, U). Ankle power showed a distinct negative period during the beginning of PP (Fig. 3T). Knee power is negative and moderate at the first part of PP, its magnitude increasing with intensity (Fig. 3S). Averaged over PP, absolute hip and shoulder power increased considerably with intensity ($p < .001$), and trunk power increased moderately ($p < .01$). Relative hip power greatly increased (from ~0 to ~41%) from LOW to MAX ($p < .001$), and relative shoulder power decreased (from ~88 to ~75%) somewhat from HIGH to MAX ($p < .001$; Table 1). At submaximal intensities, mean elbow power was positive and contributed to $P_{\text{poling-mean}}$ (~10%), but became negative at MAX. Trunk contribution tended to increase with intensity ($p = .090$).

In the RP no P_{poling} is generated and the sum of all instantaneous joint powers equals the positive rate of change in E_{body} (i.e., E_{body} increased as the body was heightened and repositioned; Fig. 2D and E). Here, most power was generated by the hip and ankle, followed by the trunk (Fig. 3R, T; Table 1). Small but significant effects of intensity were found for knee and hip relative power; hip relative power decreased from LOW to HIGH and then increased from HIGH to MAX ($p = .084$; Table 1).

4. Discussion

The purpose of this study was to examine the effect of increasing exercise intensity on the role of joint powers in DP locomotion, and the main question was whether the power contribution from the lower body joints over the movement cycle would decrease or increase when DP intensity was increased. Our findings show that increased $P_{\text{poling-mean}}$ was achieved by an increased contribution from the lower body joints, whereas the relative contribution from upper body joints decreased. This observation is in agreement with those of Bojsen-Møller et al. (2010), Rud et al. (2014) and Zoppirolli et al. (2016) who also demonstrated that increasing DP intensity was mainly done by increased lower body involvement. Somewhat surprisingly, the main increase in contribution by the lower body over the cycle occurred during PP, where hip contribution increased from ~0% at LOW to ~41% at MAX.

Since considerable (positive) work is done at the hip during PP, the idea that the lower body only does work during RP (Danielsen et al., 2015) is not supported. The substantial increase in positive hip power during PP found here may seem unexpected, but partly

reflects that repositioning of the body starts prior to the end of PP and from a deeper position with increasing intensity, as found in roller skiing DP (Lindinger, Stöggl, et al., 2009). This is also reflected in an increasing amount of positive trunk power during the final part of poling; more hip and trunk (extensor) work is responsible for this task. Still, most of body heightening occurs during RP, where hip and ankle do most of the work. However, maximum CoM height does not increase much (Danielsen et al., 2015). Although the amount of absolute work involved in repositioning during RP increases, relative power does not increase. The increases in absolute hip and ankle power during recovery also reflect that this heightening occurs faster (as CR is increased). The only small positive knee power during the final part of poling and throughout recovery indicates that little knee work is directly associated with repositioning.

4.1. Dynamic constraints

When making inferences about joint powers, one must keep in mind that in all multi-joint movements, such as DP, a unique combination of joint moments are required to achieve certain magnitudes and directions of external forces, leading to a coordinated movement. These moments may demand positive, negative or zero joint power (Jacobs & van Ingen Schenau, 1992; van Ingen Schenau, 1989). In ergometer DP, these requirements are also determined by specific constraints, in that the skier must maintain dynamic balance and position on the floor. In our set-up, during PP, F_{poling} acts in front of the CoM, creating a backward rotating moment which (on average over a cycle) must be balanced by a forward rotating moment resulting from GRF that acts behind the CoM (Fig. 2E and F). This constraint is reflected in e.g., the negative ankle power during PP at all intensities, as a plantar flexing moment during dorsal flexion aids in obtaining a GRF that acts behind the CoM. The ankle moment and power found here seem to correspond well with the high activation levels of the triceps surae muscles during dorsal flexion in this phase in roller-skiing DP (Holmberg et al., 2005). The same applies for the hip power at onset of PP, but at this joint the net moment changes from extending to flexing with increasing intensity. This is reflected by the change in direction of the GRF, which at submaximal intensities acts just in front of the hip joint but at MAX acts behind (Fig. 2D and E). This in turn requires (small) negative power at submaximal, while at MAX considerable positive power is seen (and required) during the transition from RP to PP. A similar change occurred also in knee joint dynamics, but to a lesser extent. In general, generation of F_{poling} demands a particular direction of GRF (control of balance) which clearly has implications for coordination and therefore joint dynamics. Although kinematic patterns remain largely similar (though increasing in magnitudes, Fig. 3), some dynamics essentially change. In order to generate higher F_{poling} at increasing intensities, a larger $\text{GRF}_x\text{-GRF}_y$ ratio seems required. This is partially brought about by reversed signs of hip and knee moments.

Overall, the effect of intensity on the kinematics of ergometer DP (Figs. 2 and 3) seem very comparable to roller skiing DP (Lindinger, Stöggl, et al., 2009). However, ergometer DP contains an additional degree of freedom compared to DP on roller skis or snow: ergometer DP allows for the use of horizontal frictional forces to regulate the direction of the GRF, which is not possible in roller- or on-snow skiing DP. Thus, in these latter conditions, the only way the skier can generate a moment arm for GRF about CoM is to adjust the vertical alignment between center of pressure and CoM. Alternatively, the angling and positioning of the poles is an option for control of rotational and dynamic balance, i.e., minimize the moment about CoM produced by F_{poling} . However, in general the F_{poling} vector is directed more downwards (on average) in ergometer DP than in roller- or on-snow skiing DP (more backwards through PP). Thus, effectively producing F_{poling} in these different modes of DP requires differences in coordination and joint dynamics. These mechanical dissimilarities between different modes of DP may cause differences in the solution to the requirements of dynamic constraints (control of balance and angular momentum) and in the way of achieving the mechanical goal, that is, effectively generating external power. Therefore, although the effect of intensity on the kinematics seems to be comparable between different modes of DP, this may not be the case for joint dynamics. In order to understand how these aspects may differ between DP modes, and possibly between skiers of different performance levels, future studies examining joint dynamics in on-snow or roller skiing DP as well as in skiers at different performance levels are required.

4.2. Energy flow and transfer

4.2.1. Lower extremity

During the onset of PP at MAX, when E_{body} is decreasing, the high positive hip power may reflect that the hip directly assists in generation of external power during flexion (pulling trunk down). Thus, the change from an extending to a flexing hip moment and the associated large increase in positive power is in accordance with a substantial increase in hip flexor muscle activity (Zoppirolli, Boccia, Bortolan, Schena, & Pellegrini, 2017). Otherwise, transfer of E_{body} , resulting from lower body work (in previous RP), is the main source of propulsion power during PP. This can best be understood by following the flow of mechanical energy from its source (muscle-tendon, joint power) to external work (P_{poling}) in ergometer DP: muscle-tendons in the lower body generate mechanical energy, mostly during RP, which increases the body energy. As the body then exerts force externally (F_{poling}) in PP, parts of E_{body} are transferred as the body performs this external work (e.g., Winter, 2009). In that regard, Danielsen et al. (2015) found a period of net energy absorption during the beginning of PP at submaximal intensities. This negative net (joint) work rate occurred simultaneously with high P_{poling} , suggesting that all P_{poling} originates solely from E_{body} with e.g., the upper extremities acting isometrically. This is clearly not the case: the shoulder immediately generates considerable power when F_{poling} increases (Fig. 3Q), meaning that both E_{body} transfer and active upper extremity muscle work drive propulsion immediately and simultaneously in ergometer DP. Moreover, the present analysis shows that, although the period of negative net muscle work is rather short (Danielsen et al., 2015), hip and knee power is negative also later into PP. The time point in which these powers change from negative to positive coincide with the change from trunk, hip and knee flexion to extension, that is, around the time point in which E_{body} has reached its minimum value and body heightening begins. These patterns remain similar at all intensities, and support the idea that some lower extremity muscles may be

going through a SSC during this countermovement-like action (Danielsen et al., 2015). This SSC may allow reutilization of possible excesses of E_{body} (E_{body} not transferred to P_{poling}) which otherwise would be wasted, or potentiate muscle force production.

4.2.2. Upper extremity

Previous studies have hypothesized that a SSC may occur in shoulder and elbow extensors during PP, especially in the triceps brachii (Lindinger, Holmberg, et al., 2009; Zoppirolli et al., 2013). Although typical SSC kinematics and dynamics can be seen in the elbow (i.e., flexion-extension movement coinciding with negative-positive power), we found no such clear pattern for the shoulder. The situation concerning SSC is complicated because of possible energy transfer via bi-articular muscles between the shoulder and elbow. The triceps brachii contains a bi-articular part (caput longum) that is both a shoulder and elbow extensor. In multi-joint movements, bi-articular muscles are often active with no relation to the actual angular displacement of the joints crossed (e.g., van Ingen Schenau, 1989). However, they play an essential role in distributing the net moment and power about the joints in the most effective way (Jacobs & van Ingen Schenau, 1992; van Ingen Schenau, 1989). The coinciding peaks in negative elbow and positive shoulder power are an indication of power transfer between these joints (first half of PP, Fig. 3P–Q). This may allow for a distribution of power to the joints and muscle groups that are most suitable to do work (Bobbert & van Ingen Schenau, 1988). Considering DP, allowing for power transfer to the shoulder would be beneficial if we assume that the larger, more proximally located shoulder extensor muscle groups are more suitable to do most of the active work during PP, rather than the smaller, more distally located elbow extensors. Furthermore, ensuring that the upper arm and forearm rotate in opposite directions during this first part of PP has the benefit of decreasing joint angular velocity, which increases poling time and allows more muscle work to be done over a longer time period (e.g., Bobbert, Gerritsen, Litjens, & van Soest, 1996). This movement pattern is likely also essential for an effective transfer of E_{body} into P_{poling} ('fall on the ropes or poles').

Moreover, ergometer DP does not have a typical countermovement-like action at the upper limbs, since there is no braking force present (the ropes are continuously pulled downwards/backwards, immediately generating propulsion) with no rapid impact forces. This issue is one of the main differences from other typical bouncing-ball movements involving muscle-tendon SSC, such as running (see Danielsen et al., 2015). In skiing or roller skiing DP, however, high impact forces can occur as the poles hit the ground (e.g., Stöggl & Holmberg, 2016). Although some shoulder and elbow extensor muscle-tendons may be forcefully stretched by pole-ground impact, the poles are nevertheless angled slightly backwards (Stöggl & Holmberg, 2011). Hence, propulsion is immediately generated also here, without a typical braking period that would involve (elastic) storage of decreasing E_{body} , as in typical bouncing-ball movements involving muscle-tendon SSC (e.g., running). A rapid and immediate increase in F_{poling} from onset of poling, generating very high instantaneous P_{poling} in a rather short time, seems to be essential for DP performance in general (Holmberg et al., 2005; Lindinger & Holmberg, 2011; Lindinger, Stöggl, et al., 2009; Stöggl & Holmberg, 2011). The main mechanism allowing for such high propulsion power over a short poling time, increasing recovery time, seems to be the effective use of the legs as a major source of energy generation in the RP (Danielsen et al., 2015; Holmberg, Lindinger, Stöggl, Björklund, & Müller, 2006; Lindinger, Stöggl, et al., 2009), whereas DP relying only on arm or upper-body work drastically lowers power generation capability (Hegge et al., 2016). In the PP, a certain body configuration is necessary for effective transfer of this energy, as well as for generation of additional propulsion power through active (mostly upper extremity) muscle work. To achieve this, a coordination pattern allowing for power transfer between the elbow and shoulder (and between the body and propulsion power) may prevail over SSC in explaining the kinematics and dynamics of the upper extremities in particular. For the lower extremities, however, SSC may occur in the countermovement-like transition from body lowering to body heightening since this is an effective way of reutilizing otherwise wasted energy. Nevertheless, future studies should examine these concepts regarding joint – and whole body – dynamics in roller- and on-snow skiing DP.

4.3. Concluding remarks

Regarding the potential use of horizontal GRF, ergometer DP differs from roller- and on-snow skiing DP both uphill and on the level. This may have consequences for DP coordination and dynamics. Still, ergometer DP may resemble skiing DP on the level more than uphill because of the perpendicular orientation of the (virtual) goal directed movement in relation to gravity. As in ergometer DP, in level skiing the vertical and rotational energy fluctuations (making up the most of total E_{body} , Danielsen et al. (2015)) can be distinguished from external power (to be associated with forward kinetic energy). In contrast, when skiing uphill (above a certain gradient) the vertical energy fluctuations make up most of the external work done. Therefore, the utilization of E_{body} , i.e., the use of the lower body for mechanical energy generation, will be compromised in uphill DP. While intensity generally has an increasing effect on the relative power contribution of the lower body, if intensity is increased by going up a steeper incline, the mechanism may fail. The lower efficiency of DP on a steep incline (Dahl et al., 2017) is in accordance with this rationale. On the other hand, poling times in ergometer DP resemble uphill DP more than level DP (Stöggl and Holmberg, 2016). In level DP, poling time decrease considerably with increasing speed (intensity), reaching critically low values (~ 0.25 s) which has implications for coordination, mechanics and technique (Lindinger, Holmberg, et al., 2009; Lindinger, Stöggl, et al., 2009). Future studies are warranted that examine possible similarities and differences between different modes of DP.

In the present examination of ergometer DP, the lower body's relative power contribution to propulsive power rose substantially with increasing exercise intensity, as a result of enhanced relative hip power during the PP, but not in the RP. To increase E_{body} during repositioning, considerable power is generated in the RP (and at the end of PP) by lower body joints at all intensities. During PP, a transfer of E_{body} is the main source of propulsion power. However, this transfer drives propulsion simultaneously with active (mostly upper extremity) muscle work. At higher intensities, hip dynamics essentially changed, from that of mostly absorbing at LOW to generating considerable power within PP at MAX, which may also contribute directly to P_{poling} .

Finally, a SSC may possibly be involved in hip and trunk extensors in the countermovement-like transition from body lowering to heightening, likely involving reutilization of otherwise wasted E_{body} , or potentiate muscle force production. Considering the upper extremity during PP, our data suggest that certain kinematic and dynamic patterns are related more to power distribution and transfer concepts rather than a countermovement SSC mechanism.

Acknowledgments

The authors would like to express their gratitude to the participating athletes and their coaches for their cooperation and enthusiasm during the testing sessions. The authors thank Xiangchun Tan (Department of Neuromedicine and Movement Science, Norwegian University of Science and Technology, Trondheim, Norway) for all help in the lab.

Competing interests

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. None of the authors have any competing interests to declare.

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