Master's thesis

NTNU
Norwegian University of Science and Technology

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Changes in vertical COM position and sagittal joint angles in prolonged Double Poling

Master's thesis in Physical Activity and Health

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Supervisor: Dionne Noordhof

Trondheim, June 2021

Norwegian University of Science and Technology

Faculty of Medicine and Health Sciences

Department of Neuromedicine and Movement Science

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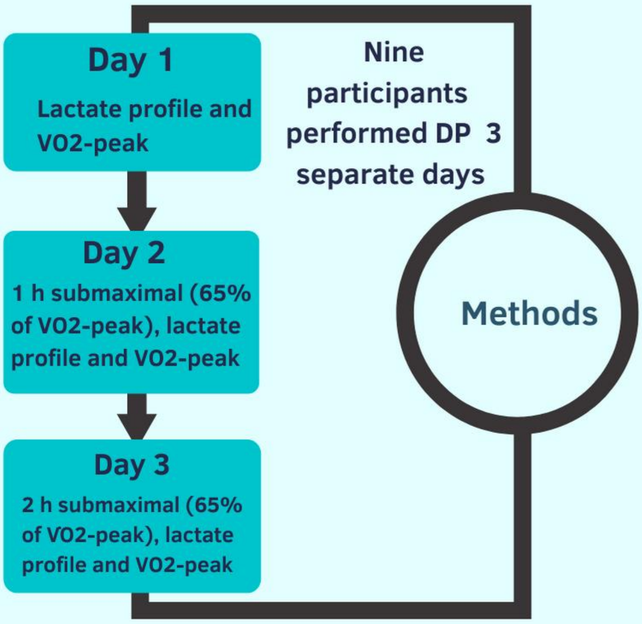
Infographic

Does fatigue affect the COM position and sagittal joint angles in prolonged Double Poling?

Background

This study investigated the effect of fatigue on the vertical COM-position and the sagittal plane joint angles in prolonged DP.



Day 1

Lactate profile and VO2-peak

Day 2

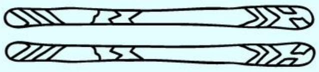
1 h submaximal (65% of VO2-peak), lactate profile and VO2-peak

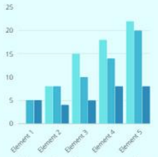
Day 3

2 h submaximal (65% of VO2-peak), lactate profile and VO2-peak

Nine participants performed DP 3 separate days

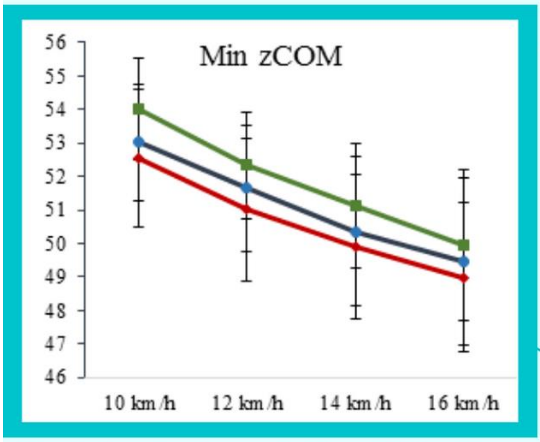
Methods



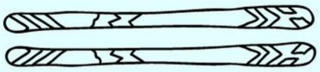


Results

Prolonged DP resulted in reduced performance indicated by a lower max speed (F(2, 7)= 3.37, p<0.05). Fatigue lowered the min zCOM (F(2, 6)= 5.87, p<0.05), and increased the maximum flexion of the hip- (F(2, 4)= 3.71, p<0.05) and knee joints (F(2, 6)= 5.29, p<0.05).



Fiure 1 shows the decreased minimum CoM-position between day 1 (green), day 2 (blue) and day 3 (3).



CONCLUSION

Two hours of prolonged DP resulted in a decline in performance, which coincided with vertical COM displacement and changes in sagittal joint angles!

Acknowledgements

I would like to thank my supervisors Dionne Noordhof and co-supervisor Knut Skovereng for their help and devotion throughout this master thesis project. I would also give my gratitude and special thank you to Cecilia Severin for her help and guidance.

Additionally, I would like to thank all the participants volunteering for this study. Even though it was some tiring days, it would not have been possible without you. Hopefully, you got some insights and knowledge about how fatigue affects performance and the causes behind it. I would also like to thank my co-partner for the data collection, Sindre Veltun. A special thanks to Tobias Ritman as well, for his help with the testing when the time was not our best friend.

Finally, I would like to thank the Center of Elite Sports Research (SenTif) for the great opportunity with this project. Is has been an educational and inspiring journey for the past year.

Håvard Lilaas

Summary in Norwegian

Introduksjon: Staking er regnet som den raskeste delteknikken i morderne, klassisk langrenn. Avstanden i konkurranse er varierende og kan være mellom 1-50 km i FIS World Cup til 40-90 km i Visma Ski Classics (VSC). At langrennsløpere trenger god utholdenhet er godt dokumentert, men det mangler kunnskap om hvordan utmattelse påvirker det vertikale tyngdepunktet og kinematikk i staking. Formålet med denne studien var derfor å undersøkte hvordan langvarig staking påvirker det vertikale tyngdepunktet og leddvinklene i sagittalplanet.

Metode: Ni deltakere (alder 22.5 år ± 2.5, høyde 180.2 cm ± 1.6, vekt 74 kg ± 2.4) gjennomførte tre dager med testing på en tredemølle på 6% stigning med rulleski. Dag 1 bestod av laktatprofil, 30 sekunders sprint på stakeergometer (PPO) og maksimalt oksygenopptak (VO_2-peak). Dag 2 og 3 bestod av en henholdsvis 1 og 2 timer submaksimal bolk etterfulgt av laktatprofil, PPO og VO_2-peak. Qualisys Track Manager (QTM) ble brukt til å måle kinematikk i staking underveis og ble videre analysert i Visual 3D (V3D) og MatLab. Statistiske analyser ble gjennomført i IBM SPSS 25.0.

Resultat: Langvarig staking resulterte i en nedgang i prestasjon som er definert som nedgang i maks hastighet ($F(2, 7)= 3.37$, $p<0.05$). Utmattelse førte til en lavere posisjon av zCOM ($F(2, 6)= 5.87$, $p<0.05$), samt økt maksimal fleksjon i henholdsvis hofte- ($F(2, 4)= 3.71$, $p<0.05$) og kneleddene ($F(2, 6)= 5.29$, $p<0.05$).

Konklusjon: To timer med langvarig staking resulterte i en nedgang i prestasjon, som henger sammen med forskyvningen av det vertikale tyngdepunktet endringen i leddvinklene i sagittalplanet.

Abstract

Introduction: Double poling is considered the fastest classic sub-technique in modern day Cross-Country Skiing (XCS). The distance in competition vary from 1-50 km in the FIS World Cup to 40-90 km in the Visma Ski Classics (VSC). Due to that, the sport requires the ability to perform over longer periods. However, the effects of fatigue on center of mass (COM) and double poling (DP) kinematics is not well investigated. This study investigated the effect of fatigue on the vertical COM-position and the sagittal plane joint angles in prolonged DP. Prolonged DP will most likely result in fatigue, which will influence the vertical COM-position and the sagittal plane joint angles.

Methods: Nine male participants (22.5 y ± 2.5, 180.2 cm ± 1.6, 74 kg ± 2.4) performed DP at 6% incline on a treadmill on 3 separate days. Day 1 consisted of lactate profile, peak power output (PPO) and peak oxygen uptake (VO_2-peak). Day 2 and 3 consisted of 1- and 2 h submaximal DP (65% of VO_2-peak), lactate profile, PPO and VO_2-peak. DP kinematics were captured using Qualisys Track Manager (QTM) and analyzed in Visual 3D (V3D). Statistical analysis was conducted in IBM SPSS 25.0.

Results: Prolonged submaximal DP resulted in a decline in performance indicated by a lower max speed ($F(2, 7)= 3.37$, $p<0.05$). Fatigue lowered the min zCOM ($F(2, 6)= 5.87$, $p<0.05$), and fatigue increased the maximum flexion of the hip- ($F(2, 4)= 3.71$, $p<0.05$) and knee joints ($F(2, 6)= 5.29$, $p<0.05$).

Conclusion: Two hours of prolonged DP resulted in a decline in performance, which coincided with vertical COM displacement and changes in sagittal joint angles.

List of abbreviations

XCS – Cross-Country SKiing

DP – Double Poling

zCOM – Vertical Center of Mass

min/max zCOM – Lowest/Highest position of Vertical Center of Mass

ROM – Range of Motion

$\dot{V}O_2$-peak – Change in peak oxygen uptake

PPO – Peak Power Output

mL – Milliliters

CHO – Carbohydrate

R/L – Right/Left

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1.1 Introduction

Cross-country skiing (XCS) is a challenging sport that has high demands on endurance, strength, and technique. In all-round XCS (FIS World Cup), the distance in competition can vary from 1-50 km in both classic- and skating technique. Over the last decades, the popularity of the longest distances has increased, which has led to the Visma Ski Classics (VSC) (Sandbakk & Holmberg, 2017), VSC is a series of long-distance (>40 km) ski races performed in more flat terrain compared to all-round XCS (Torvik et.al., 2021). This has led to an increased specialization in double poling (DP), which is considered the fastest, classic sub-technique in modern day XCS (Nilsson et.al., 2012).

The DP technique is commonly divided into a poling phase and a swing phase. The poling phase is defined as the period from pole plant to pole off, which is the phase where the propulsive pole force is attained. The swing phase is defined as the period from pole off to the consecutive pole plant, which repositions the body to the following poling phase. These two phases defines one DP-cycle (Danielsen et.al., 2015 & 2019).

It has been shown earlier that DP requires well-developed upper-body strength and endurance capacity, due to the large propulsion through the poles (Skattebo et.al., 2019). However, an optimal force transfer to the ground via the poles cannot only be attained by the arm, shoulder, and trunk muscles, but also by the active movement of the legs (Zoppirolli et.al., 2015 & Danielsen et.al., 2015). During the poling phase, an important part of the pole propulsion may come from a transfer of body mechanical energy, i.e., from work done by the legs in the previous swing phase (Danielsen et.al., 2015). The activation of the legs during flexion and extension of the hip, knee, and ankle joints, contributes to stabilize, position, and reposition the body center of mass (COM) during each DP-cycle (Holmberg et.al., 2006). During the swing phase, the legs generate power that result in a higher COM (Holmberg et.al., 2006 & Zoppirolli et.al., 2015). Elevation and forward positioning of the COM during the beginning of the poling phase leads to increased pole force. By that, the skiers can use both their body mass and gravity to increase the propulsive pole force (Zoppirolli et.al., 2015). With increased pole force, hip and knee angles decreases at pole plant, hip and knee flexion range of motion (ROM) increases and hip and knee extension ROM increases during the swing phase (Holmberg et.al., 2006 & Zoppirolli et.al., 2015). This contribution of the legs increases with intensity and by minimizing the involvement of the legs, power output and performance decreases (Holmberg et.al., 2006, Lindinger et.al., 2009).

Zoppirolli et.al. (2015) found that high-level skiers showed more forward incline of the body, smaller COM vertical displacement range and greater hip and knee joint extension during the poling phase than lower performing skiers. Due to the long distances during certain competitions, the effects of fatigue may be a crucial factor for the overall performance. By that, the vertical COM position and sagittal plane joint angles plays an important role when performing prolonged DP. Despite that, very few studies have investigated the effect of fatigue on DP kinematics in XCS. The same research group investigated the effect of a short incremental time to exhaustion on full-body kinematics. They concluded that the skiers maintained the same joint angles and COM kinematics, despite development of metabolic and localized fatigue (Zoppirolli et.al. 2016). However, they speculate if a longer period of fatigue might alter DP kinematics, either directly by changing the coordination of movements or indirectly by reducing muscle force. There is a lack of knowledge on the effects of fatigue on COM and changes in the sagittal joint angles in DP. Therefore, this study will investigate the effects of fatigue on vertical COM-position and sagittal plane joint angles in prolonged DP. The hypothesis to be tested is that fatigue will lower the vertical COM-position and decrease the sagittal plane joint angles, leading to an unfavorable utilization of force production.

2.1 Methods

2.2 Participants

Nine male all-round cross-country skiers (age 22,6 ± 2.5 y, height 180.2 ± 1,6 cm, body mass 74. ± 2.4 kg) competing at national and international level participated in this study. The study was registered and approved by the Norwegian center for research data (NSD). Before the start of the study, all participants received written information about the purpose of the study and the potential risks associated with it, after which they provided written informed consent. All participants were familiar with roller skiing from their daily training. They could withdraw at any time without any given reason.

The food intake before testing were standardized and the participants had to restrict their caffeine consumption (no caffeine 3 hours before test). The participants could not perform high intensity training the day before test and the order of day 2 and day 3 were randomized.

2.3 Experimental protocol

The experimental protocol consisted of 3 days of testing per participant, with minimum 24 hours between each test day. On day 1, the participants completed a blood-lactate profile, a 30-second peak power output (PPO) test and peak oxygen uptake ($\dot{V}O_2$-peak) test in DP. On day 2 and 3, the participants performed a submaximal test in DP for 1 and 2 hours respectively, before repeating the same tests as on day 1.

2.3.1 Day 1

Day 1 consisted of 10-minute warm up at 3% incline and 12 km/h on the treadmill. Directly after the warm up, a lactate profile test (inclination 6% and speed 10 km/h) was performed. The speed increased by 2 km/h every 5 min until a blood lactate concentration increased with 1.5 mmol or $\geq$4 mmol$\cdot$L^{-1} was reached. The blood lactate sample was taken from the fingertip. After the lactate profile, a 5 min active recovery at 3% inclination and a speed of 12 km/h was completed. Then, a PPO and $\dot{V}O_2$-peak were performed to determine peak power and $\dot{V}O_2$-peak. Between the PPO and $\dot{V}O_2$-peak, the participants had an active recovery for 10 min at 3% incline and a speed of 12 km/h. The $\dot{V}O_2$-peak started at 6% inclination and speed of 10 km/h, which increased by 1 km/h, every minute, until exhaustion. The physiological data retrieved from the lactate profile test and PPO were used for another project. The physiological data collected from the $\dot{V}O_2$-peak were in this study only used to calculate the speed equal to 65% of $\dot{V}O_2$-peak in day 1.

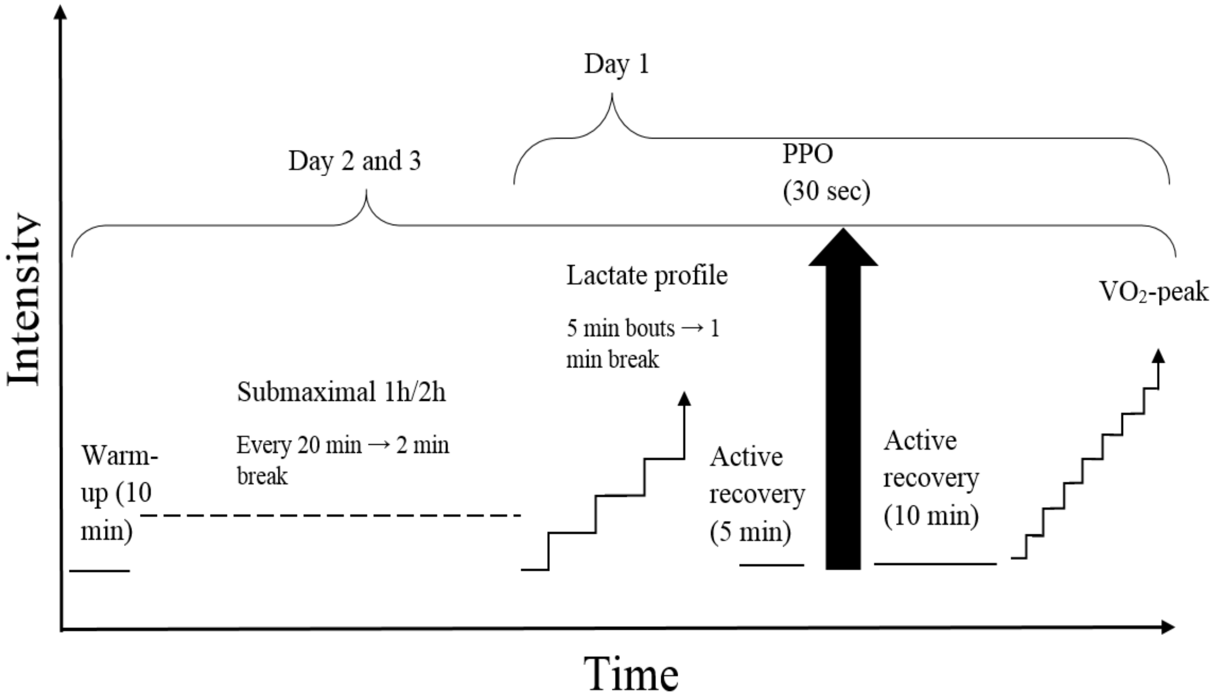

Figure 1.1: Protocol. PPO and VO_2-peak data were used for another study

2.3.2 Day 2 and 3

Day 2 and 3 consists of the same tests as day 1, but with an additional submaximal bout. On day 2, the participants performed a 1-hour submaximal DP bout. On day 3 the participants performed a 2-hour submaximal bout. Before the 1- and 2-hour submaximal bout, the participants did the same warm-up routine as on day 1. The submaximal bout was performed at 6% inclination and speed equal to 65% of $\dot{V}O_2$-peak determined individually using the data collected from the $\dot{V}O_2$-peak in day 1. Directly after the submaximal bout, the participants performed the same tests as in day 1.

2.3.3 Nutrition

During the submaximal tests, the treadmill was stopped every 20 minute to measure glucose levels and to drink 250 mL of isotonic sports drink (Enervit Isotonic Drink Lemon/Orange, Milano, Italy). The participants had to drink a total of 750 mL water added with 45 g carbohydrate (CHO) per hour to prevent hypoglycemia and maintain fluid balance during the submaximal tests (Thomas et al., 2016).

2.4 Instruments and Materials

A 5x3m motor driven treadmill was used for the roller ski tests (Forcelink Technology, Zwolle, Netherlands). To minimize variations in rolling resistance (resistance category 2), all participants used the same pair of roller skis (IDT Sports, Lena, Norway). Due to Covid-19, the participants used their own poles, with their preferred height. They could not alter this between tests. The poles had 5 cm special carbide tips (Madshus UHM 100, Biri, Norway). The participants were secured with a safety harness connected to an emergency brake.

2.5 Kinematic Measurements

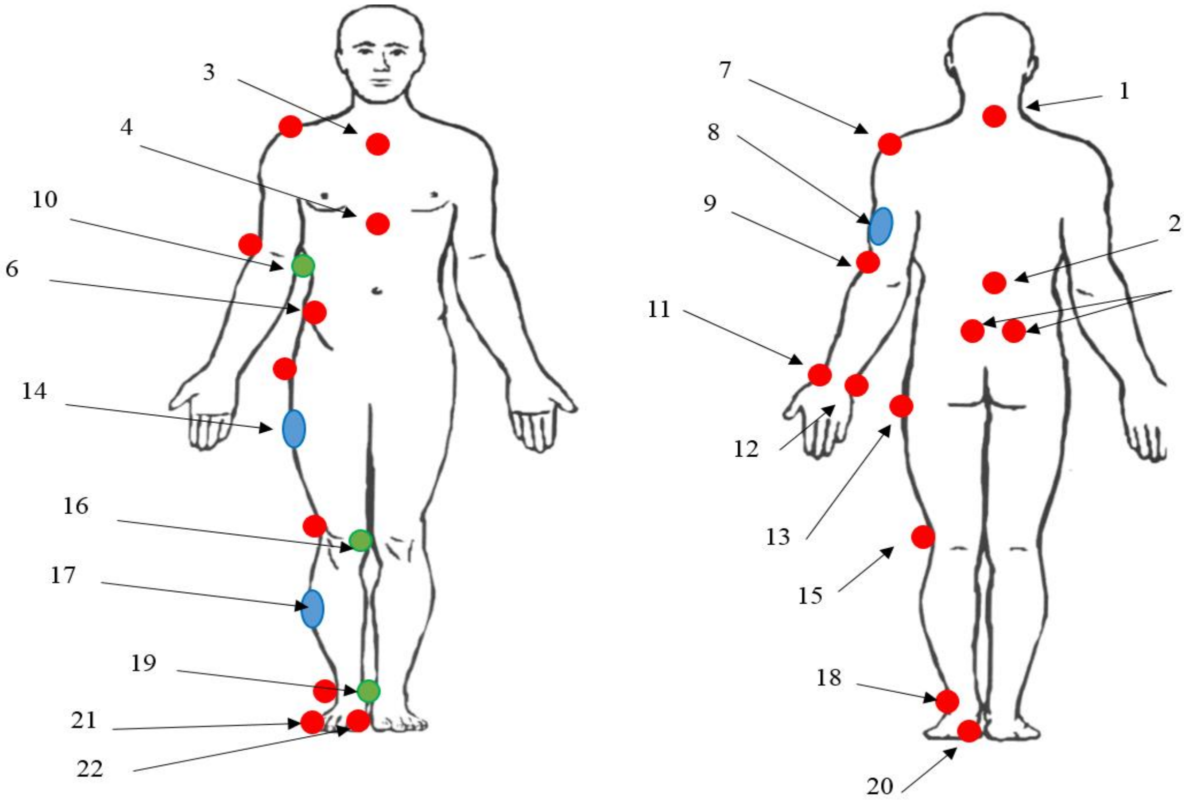

Figure 1.2: Marker placement. Red: Base markers, blue: thigh and shank clusters, green: markers included in statical trials to determine joint center.

Kinematic data were collected using reflective markers and were captured by eight Oqus infrared cameras (Qualisys AB, Gothenburg, Sweden) at a sampling frequency of 250 Hz. A full-body marker set up was used, consisting of 60 markers in total. The same researcher placed the reflective markers on the participant’s skin with double-sided tape (3 M, USA) on the anatomical landmarks illustrated in Figure 1.2 and Table 1.1. Six markers were placed on the poles and roller skis to measure and identify DP-cycles. One marker was placed on the lateral side of each pole, 5 cm below the handle and one marker placed on the lateral side of the pole tip. One marker was attached 1 cm behind the front wheel on each roller ski.

Table 1.1: Marker definition of anatomical landmarks. R/L= Right/Left. Cluster = 3-4 markers

Marker	**Location**
1	Over the spinous process of the 7th cervical vertebrae
2	Over the spinous process of the 12th thoracic vertebrae
3	In the middle of the Manubrium
4	On the tip of the Xiphoid process
5	R/L Posterior superior iliac spine
6	R/L Anterior superior iliac spine
7	R/L acromion process. Most lateral aspect of scapula on top of shoulder
8	R/L cluster middle of upper arm
9	R/L lateral epicondyle of humerus
10	R/L medial epicondyle of humerus
11	R/L lateral wrist
12	R/L medial writst
13	R/L greater trochanter
14	R/L cluster middle of lateral surface of thigh
15	R/L lateral femoral epicondyle
16	R/L medial femoral epicondyle
17	R/L cluster middle of lateral surface of shank (calf)
18	R/L lateal malleolus (ankle)
19	R/L medial malleolus
20	R/L heel (most posterior surface of calcaneus, on boot)
21	R/L first metatarsal
22	R/L 5th metatarsal

Each recording session took 30 seconds. During the lactate profile test, one measurement were completed after 1 min each step until the lactate threshold ≥ 4 mmol·L-1 was reached. The coordinate system was calibrated according to the manufacturer's recommendation (treadmill 0°, the positive x-axis was the longitudinal axis of the treadmill, the y-axis was side to side direction across the treadmill, and the z-axis perpendicular to the ground). After calibration and before warm-up the participants completed a static trial in the anatomical position.

2.6 Data Analysis

Performance is determined as peak speed (Vpeak; mean speed attained during the last minute of VO_2-peak). The kinematic data was collected in Qualisys and further exported in to Visual 3D, v6.01.36 (C-Motion Inc., Germantown, USA) for analysis. The kinematic data were filtrated using a 4th order low pass Butterworth filter (15Hz), and joint angles were calculated according to Wu et.al. (2002 & 2005) based on the static capture. Regarding the kinematic data of the poles, symmetry is assumed, and the distal marker on the right pole is used to identify DP-cycles and pole on/off. Vertical COM displacement (zCOM), joint angles and poling cycles were exported to MatLab (MatLab 2020b, The MathWorks, Inc., Natick, MA, USA) for further analysis. The COM were calculated using individual body mass and segment lengths according to de Leva (1996) and Danielsen et.al. (2015). zCOM is expressed as % of body height based on the paper of Zoppirolli et.al. (2015). COM and joint angles were time-normalized (0-100%) of a cycle. Maximum and minimum values of zCOM were used to calculate the zCOM range. Joint flexion is determined as positive values and joint extension is determined as negative values according to the right hand rule. The data was further exported in Microsoft Excel 2013 (Microsoft 365, Redmond, WA, USA), where the figures and tables were made.

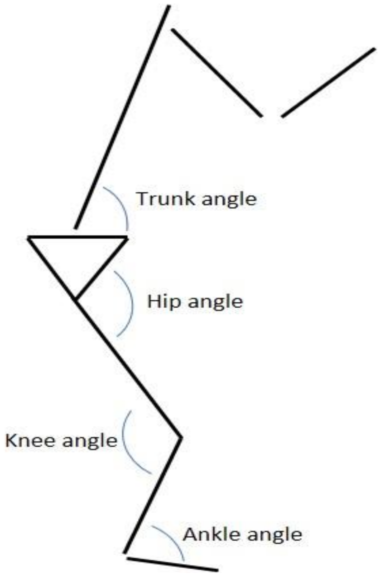

Figure 1.3: Sagittal joint angle definitions

2.7 Statistical Analysis

Statistical analyses were performed using SPSS 25.0 (SPSS Inc., Chicago, IL, USA). The data was checked for normality with the Shapiro-Wilk test and are presented as mean and standard deviation (±SD). Repeated measures analyses of variances (ANOVA) was used to assess the effect of prolonged submaximal DP (test days) on performance, zCOM and joint angles. Pearson correlation was used to determine correlations between zCOM and decrease in performance. Statistical significance was set to $p<0.05$ and 95% confidence intervals were calculated. Cohen's D was used as effect size (d) and calculated in Microsoft Excel 2013. Effect sizes were interpreted as follows: small effect d= 0.2-0.5, moderate effect d= 0.5-0.8, large effect d= >0.8 (Cohen, 1988).

3.1 Results

3.2 Effects on Performance

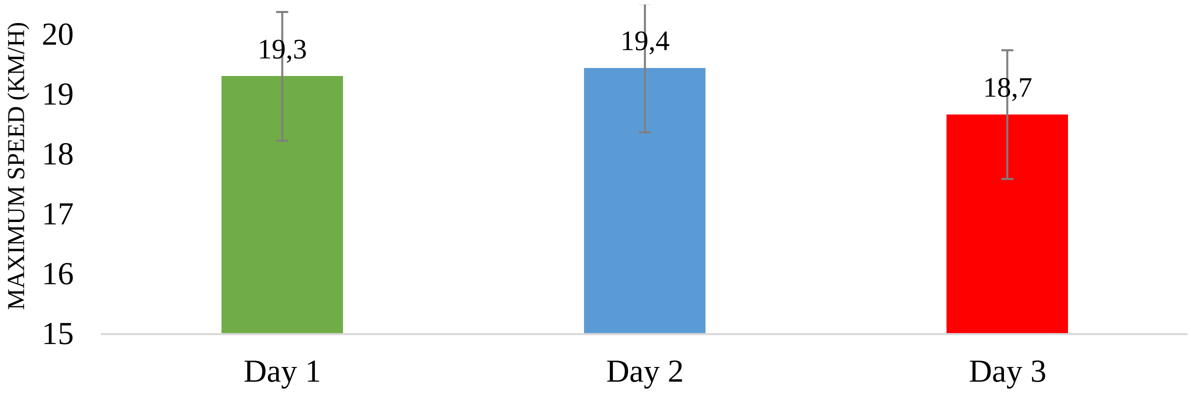

Figure 2.1: Decrease in performance. The data is presented as mean km/h ± SD

A significant effect of fatigue on performance was found (F(2, 7)=3.37, $p<0.05$). The results also indicate that prolonged DP is larger on day 3 (F(2, 16)= 3.95, $p<0.05$). A significant interaction effect was found (F(2,16)= 3.95, $p<0.04$). There was a decrease in performance as indicated by a lower max speed on day 3 compared to day 2 (F(1,8)= 7.05, p=0.029, d= 0.58) (figure 2.1). There was no significant difference in peak speed between day 1 and day 2 (p=0.52), and day 1 and day 3 (p=0.12).

3.3 Effects on Center of Mass

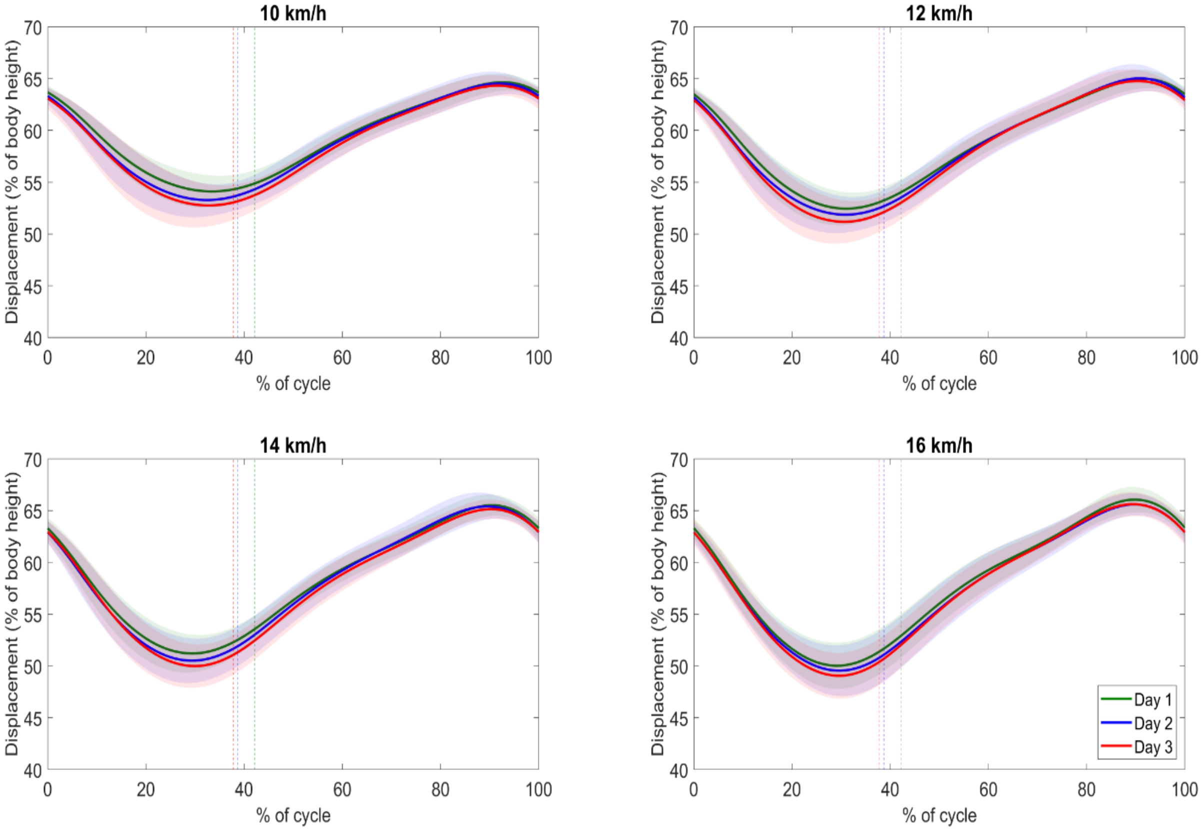

Figure 2.2: Vertical displacement of COM during one DP-cycle. Vertical line: Pole off. Top left: 10 km/h, top right: 12 km/h, bottom left: 14 km/h, bottom right: 16 km/h

Figure 2.3 shows how the highest position, lowest position and overall movement of the COM changed with the different speeds over the three days. A significant effect of fatigue on min zCOM were found (F(2, 6)= 5.87, p= 0.039). The effect of prolonged DP is larger on the higher intensities (14 km/h & 16 km/h) (F(2, 14)= 10.35, p= 0.002). Min zCOM decreased significantly between day 1 and day 2 at 12 km/h (52.33% ± 1.60 to 51.64% ± 1.90, F(1, 7)= 7.14, p=0.032, d= 0.33) and 14 km/h (51.12% ± 1.85 to 50.36% ± 2.24, F(1, 7)= 12.25, p=0.010, d= 0.31) (figure 2.3). It also decreased between day 1 and day 3 at all speeds (10 km/h: 54.02% ± 1.52 to 52.54% ± 2.07, F(1, 7)= 7,97, p= 0.021, d= 0.70, 12 km/h: 52.33% ± 1.60 to 51.01% ± 2.14, F(1, 7)= 13.40, p=0.008, d= 0.59, 14 km/h: 51.12% ± 1.85 to 49.89% ± 2.14, F(1, 7)= 16.26, p= 0.005, d= 0.52 and 16 km/h: 49.96% ± 2.24 to 48.99% ± 2.23, F(1, 5)= 9.61, p= 0.027, d= 0.35). Between day 2 and day 3 min zCOM decreased at 12 km/h (51.64% ± 1.90 to 51.01% ± 2.14, p=0.033, d= 0.26) (Figure 2.3).

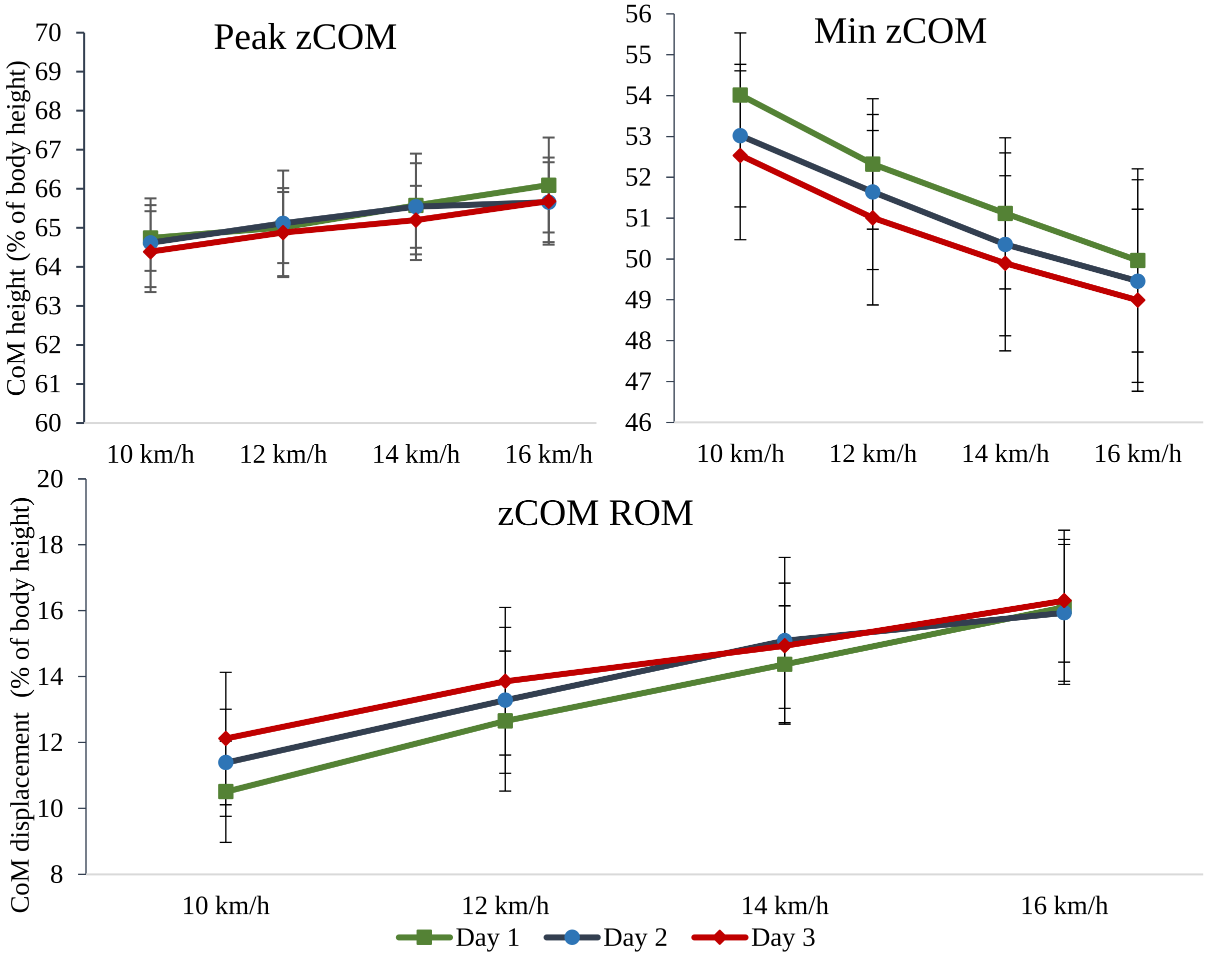

Figure 2.3: Changes in CoM-position between day 1, day 2 and day 3. The data is presented as mean ± SD. Top left: Vertical displacement maximum value. Top right: Vertical displacement minimum value. Below: Vertical displacement range

A significant effect of fatigue on peak zCOM were found (F(2, 4)= 15.51, p= 0.013). The effect of prolonged DP was larger at 16 km/h (F(2, 10)= 12.85, p= 0.002). Peak zCOM differed significantly between day 1 and day 2 and between day 1 and day 3 at 16 km/h (day 1 66.10% ± 1.22, day 2 65.66% ± 1.02, F(1, 5)= 34.47, p=0.002, d= 0.31, day 3 65.68% ± 1.12, F(1, 5)= 9.95, p=0.025, d= 0.29) (Figur 2.3). A significant effect of fatigue on zCOM ROM (F(2, 6)= 10.79), p<0.05). Prolonged DP had larger effect at 12 km/h (F(2, 14)= 10.28, p= 0.002). Between day 1 and day 3 zCOM ROM increased at 10 km/h (10.51% ± 1.53 to 12.12% ± 2.01, F(1, 7)= 5.89, p= 0.046, d= -0.77) and 12 km/h (12.65% ± 2.12 to 13.86% ± 2.24, F(1, 7)= 14.94, p= 0.006, d= 0.46). zCOM ROM increased between day 2 and day 3 at 12 km/h (13.28% ± 2.22 to 13.86% ± 2.24, F(1, 7)= 18.07, p=0.004, d= -0.21) (Figure 2.3).

3.3 Effects on joint angles

No significant effect of fatigue on trunk angle was found. However, a significant effect of fatigue on hip extension were found (F(2, 4)= 6.99, p= 0.049). The results indicate that prolonged DP had larger effect at higher speeds (F(2, 10)= 5.94, p= 0.02). Hip extension increased at 16 km/h (F(1, 7)= 6.02, p<0.05, d= -0.89) between day 1 and day 3. Between day 2 and day 3, hip extension increased at 16 km/h (p<0.05, F(1)= 7.63, d= -0.68) (Table 2.1). There was a significant effect of fatigue on hip flexion (F(2, 4)= 3.71, p<0.05). The effect of fatigue on hip flexion was significant (F(2, 4)= 3.71, p= 0.032). The effect of prolonged DP was larger at 16 km/h (F(2, 10)= 4.90, p= 0.033). Hip flexion increased at 14 km/h (F(1, 5)= 6.02, p<0.05, d= -0.66) and 16 km/h (F(1, 5)= 6.76, p= 0.048, d= -0.89) between day 1 and day 3. Between day 2 and day 3, hip flexion increased at 16 km/h (F(1, 5)= 16.37, p= 0.010, d= -0.64) (Table 2.1). A significant effect of fatigue on hip ROM was found (F(2, 6)= 8.25, p= 0.019). The effect of prolonged DP on hip ROM was larger at 10 km/h (F2, 14)= 4.45, p= 0.032). Hip ROM differed significantly between day 1 and day 2 at 12 km/h (F(1, 7)=5.99, p<0.05, d= -0.19). Between day 1 and day 3, hip range of motion increase at 10 km/h (F(1, 7)= 5.81, p<0.05, d= -0.62), 12 km/h (F(1)=7.52, p= 0.029, d= -0.36) and 16 km/h (F(1)=7.99, p<0.05, d= -0.79) (Table 2.1).

A significant effect of fatigue on knee flexion (max) were found (F(2, 06)= 5.29, p= 0.047). Larger effect of prolonged DP at 16 km/h (F(2, 10)= 5.25, p= 0.028). Max knee flexion increased between day 1 and day 3 at 14 km/h (F(1, 7)= 6.33, p<0.05, d= -0.43). Between day 2 and day 3 max knee flexion increased at 16 km/h (F(1, 5)= 11.68, p<0.05, d= -1.44) (Table 2.2). There were no significant effect of fatigue on ankle dorsi- and plantar flexion. However, there was a significant increase in range of motion at 10 km/h between day 1 and day 2 (F(1)=7.05, p<0.05, d= -0.56) (Table 2.2).

Table 2.1: Changes in trunk- and hip joint angles. The data is presented as mean ± SD. ROM: Range of motion

			Day 1	Day 2	Day 3	Day 1 vs day 2		Day 1 vs day 3		Day 2 vs day 3	
		n				p-value	d	p-value	d	p-value	d
Trunk flexion (°)	10 km/h	8	27.7 ± 6.3	27.3 ± 9.7	26.3 ± 10.0	0.88	0.03	0.57	0.14	0.39	0.09
	12 km/h	9	29.1 ± 4.5	31.1 ± 7.7	30.9 ± 8.2	0.38	-0.28	0.43	-0.24	0.89	0.02
	14 km/h	9	29.5 ± 7.2	31.9 ± 11.6	31.2 ± 10.9	0.30	-0.22	0.46	-0.17	0.69	0.05
	16 km/h	6	33.9 ± 8.5	35.7 ± 13.7	34.7 ± 14.1	0.53	-0.14	0.812	-0.06	0.55	0.06
Trunk extension (°)	10 km/h	8	2.5 ± 6.6	3.5 ± 10.2	4.6 ± 11.9	0.59	-0.10	0.34	-0.20	0.21	-0.09
	12 km/h	9	2.3 ± 5.9	3.1 ± 10.3	3.8 ± 11.9	0.67	-0.08	0.54	-0.15	0.47	-0.05
	14 km/h	9	3.7 ± 6.4	3.6 ± 10.0	5.1 ± 11.5	0.99	-0.00	0.44	-0.15	0.19	-0.12
	16 km/h	6	4.1 ± 7.7	3.9 ± 11.6	5.5 ± 12.7	0.94	0.01	0.52	-0.12	0.123	-0.11
ROM (°)	10 km/h	8	29.1 ± 7.1	30.5 ± 6.6	32.4 ± 5.8	0.30	-0.16	0.07	-0.40	0.10	-0.24
	12 km/h	9	32.8 ± 7.1	34.6 ± 5.9	35.5 ± 6.8	0.12	-0.23	0.01	-0.32	0.47	-0.12
	14 km/h	9	33.3 ± 7.6	34.4 ± 6.6	35.9 ± 5.5	0.30	-0.13	0.07	-0.31	0.23	-0.20
	16 km/h	6	39.0 ± 8.6	39.7 ± 6.1	38.9 ± 5.2	0.75	-0.07	0.98	0.01	0.64	0.10
Hip flexion (°)	10 km/h	8	63.3 ± 7.1	65.5 ± 10.0	70.1 ± 7.9	0.44	-0.22	0.06	-0.75	0.16	-0.40
	12 km/h	9	68.0 ± 8.3	69.3 ± 10.2	74.0 ± 7.7	0.63	-0.12	0.09	-0.61	0.15	-0.41
	14 km/h	9	71.8 ± 7.2	72.6 ± 10.7	77.8 ± 8.1	0.75	-0.08	0.04	-0.66	0.11	-0.43
	16 km/h	6	72.7 ± 4.7	72.6 ± 9.9	80.3 ± 10.1	0.95	0.02	0.05	-0.89	0.01	-0.64
Hip extension (°)	10 km/h	8	18.7 ± 4.9	18.5 ± 8.1	22.5 ± 6.7	0.91	0.03	0.25	-0.55	0.14	-0.42
	12 km/h	9	17.7 ± 4.	16.5 ± 7.4	21.3 ± 6.1	0.64	0.20	0.23	-0.61	0.09	-0.57
	14 km/h	9	18.9 ± 5.1	17.4 ± 8.4	22.4 ± 6.3	0.52	0.19	0.12	-0.53	0.09	-0.53
	16 km/h	6	16.7 ± 4.5	16.4 ± 7.5	22.4 ± 6.3	0.89	0.04	0.05	-0.89	0.04	-0.68
ROM (°)	10 km/h	8	43.4 ± 6.0	46.0 ± 4.9	47.6 ± 4.5	0.10	-0.38	0.05	-0.62	0.19	-0.26
	12 km/h	9	49.5 ± 7.0	51.3 ± 8.0	52.3 ± 4.9	0.04	-0.20	0.03	-0.36	0.48	-0.12
	14 km/h	9	52.3 ± 4.5	55.2 ± 7.0	54.8 ± 4.9	0.08	-0.43	0.08	-0.45	0.78	0.04
	16 km/h	6	54.4 ± 3.7	55.6 ± 5.7	58.4 ± 4.7	0.39	-0.20	0.04	-0.80	0.17	-0.43

Table 2.2: Changes in knee and ankle joint angles. The data is presented as mean ± SD. ROM: Range of motion.

			Day 1	Day 2	Day 3	Day 1 vs day 2		Day 1 vs day 3		Day 2 vs day 3	
		n				p-value	d	p-value	d	p-value	d
Knee flexion (max) (°)	10 km/h	8	43.9 ± 6.9	44.1 ± 6.2	46.8 ± 3.5	0.93	-0.02	0.27	-0.39	0.30	-0.40
	12 km/h	9	49.2 ± 9.7	50.6 ± 11.2	53.2 ± 7.9	0.41	-0.11	0.09	-0.36	0.36	-0.21
	14 km/h	9	51.8 ± 7.5	52.8 ± 8.6	55.6 ± 6.8	0.37	-0.11	0.04	-0.43	0.25	-0.28
	16 km/h	6	54.6 ± 4.7	52.5 ± 3.3	58.2 ± 3.3	0.19	0.41	0.16	-0.70	0.02	-1.44
Knee flexion (min) (°)	10 km/h	8	15.8 ± 5.6	16.9 ± 4.4	19.1 ± 6.1	0.66	-0.16	0.33	-0.47	0.34	-0.37
	12 km/h	9	15.9 ± 4.9	16.3 ± 4.0	19.6 ± 5.9	0.84	-0.07	0.29	-0.57	0.15	-0.56
	14 km/h	9	15.5 ± 3.4	15.9 ± 4.3	18.5 ± 6.9	0.74	-0.10	0.25	-0.49	0.32	-0,38
	16 km/h	6	15.3 ± 4.0	14.9 ± 4.5	19.4 ± 7.9	0.61	0.08	0.23	-0.59	0.16	-0.62
ROM (°)	10 km/h	8	28.6 ± 3.3	26.6 ± 5.5	28.0 ± 5.1	0.11	0.39	0.68	0.11	0.43	-0.22
	12 km/h	9	33.6 ± 7.2	34.4 ± 10.6	33.4 ± 7.9	0.69	-0.07	0.78	0.03	0.60	0.08
	14 km/h	9	35.7 ± 6.8	37.1 ± 8.4	36.6 ± 10.2	0.29	-0.16	0.73	-0.09	0.78	0.05
	16 km/h	6	38.4 ± 3.1	37.8 ± 4.3	38.9 ± 4.8	0.67	0.13	0.75	-0.12	0.09	-0.21
Ankle dorsiflexion (°)	10 km/h	8	1.7 ± 5.6	1.9 ± 3.7	1.3 ± 4.8	0.80	-0.05	0.82	0.05	0.50	0.14
	12 km/h	9	3.3 ± 5.2	2.9 ± 3.9	2.4 ± 5.0	0.82	0.05	0.59	0.14	0.54	0.11
	14 km/h	9	5.3 ± 6.6	5.1 ± 4.6	4.8 ± 6.3	0.87	0.03	0.76	0.07	0.79	0.05
	16 km/h	6	5.2 ± 6.2	4.2 ± 4.3	3.5 ± 4.6	0.63	0.15	0.55	0.24	0.62	0.11
Ankle plantarflexion(°)	10 km/h	8	10.8 ± 5.2	11.9 ± 4.0	12.9 ± 4.1	0.51	-0.19	0.27	-0.36	0.48	-0.20
	12 km/h	9	11.2 ± 5.2	12.3 ± 5.1	12.8 ± 5.3	0.56	-0.18	0.46	-0.26	0.76	-0.08
	14 km/h	9	11.2 ± 5.8	10.9 ± 3.5	12.1 ± 5.4	0.81	0.06	0.65	-0.12	0.41	-0.23
	16 km/h	6	15.2 ± 4.7	13.3 ± 3.5	14.5 ± 5.6	0.25	0.37	0.69	0.12	0.53	-0.23
ROM (°)	10 km/h	8	12.2 ± 3.3	14.6 ± 3.6	13.9 ± 3.7	0.03	-0.56	0.31	-0.40	0.67	0.15
	12 km/h	9	13.7 ± 2.3	14.4 ± 4.1	14.9 ± 3.6	0.71	-0.18	0.43	-0.35	0.56	-0.12
	14 km/h	9	16.1 ± 1.8	16.3 ± 3.0	16.2 ± 4.0	0.89	-0.06	0.97	-0.02	0.93	0.03
	16 km/h	6	20.7 ± 7.1	17.7 ± 3.9	18.2 ± 2.4	0.18	0.39	0.39	0.34	0.65	-0.12

4.1 Discussion

The current study investigated the effects of prolonged DP on zCOM-position and sagittal plane joint angles. The hypothesis was that fatigue lowered the zCOM-position and decreased the sagittal plane joint angles, leading to an unfavorable position to produce force. The main results were (1) prolonged submaximal DP resulted in a decline in performance (Figure 2.1); (2) fatigued lowered min zCOM (Figure 2.3); and (3) fatigue increased maximum flexion of the hip- and knee joints. These results indicate that fatigue affects the zCOM position and sagittal joint angles, which ultimately leads to decreased performance.

4.2 Differences in performance

Prolonged DP decreased the performance, which means that the participants are not able to achieve the same maximum speed when fatigued. There were no significant decrease in performance between day 1 and day 2. The results indicates that the performance increased between day 1 and day 2 and decreased between day 2 and day 3 (Figure 2.1). Some of the participants reported verbally that they are not so familiar with either performing DP for several consecutive hours and roller skiing on a treadmill. The differences between day 1 and day 2 may be caused by the participants getting more comfortable and familiar with DP on the treadmill, and by that are able to increase the maximum speed. The decrease in performance between day 2 and day 3 may be caused by the increased duration. Noordhof et.al (2020) showed that prolonged DP decreased the performance, which is arguably the same findings as in this present study. Fatigue has been proved to decrease the performance in XCS (Zory et.al. 2009 & Zoppirolli et.al. 2016) due to progression in localized muscle fatigue. With increased fatigue, Zoppirolli et.al. (2016) showed a reduced capacity to produce propulsive force, which is shown to decrease performance (Holmberg et.al., 2006). In addition to fatigue, the reported “lack” of specialization in DP may be a factor for the decrease in performance after 2 hours of prolonged DP. A study conducted by Skattebo et.al. (2019) compared performance between all-round skiers and long-distance skiers. They argue that age, specialization and competition duration are important factors when performing prolonged DP, which favors the long-distance skiers. The participants in our study are considered young (age 22,6 ± 2.5 y), which may part of the decreased performance.

4.3 Changes in zCOM

The results in this present study indicates that fatigue is affecting zCOM-position by lowering the minimum zCOM (Figure 2.3). The participants adapted a more flexed hip- and knee joints when fatigued, meaning that the sagittal joint angles decreased after 2 hours of prolonged DP. Based on these results, increased hip- and knee joints leads to lower minimum zCOM-position and in particular at the end of the poling phase (Figure 2.2). The lower minimum zCOM indicates that the participants go deeper when they are fatigued, and the results of day 3 compared to day 1 suggests that fatigued participants were unable to maintain the same upright body position (figure 2.3) (Holmberg et.al., 2005). Decreased pole force is associated with decreased performance, as stated earlier. However, Zoppirolli et.al. (2015) showed that better skiers were able to maintain their minimum zCOM position to a greater extent. Zoppirolli et.al. (2015) states that limited lowering of min zCOM is advantageous for the energetic cost of DP. Lowering of the min zCOM is affecting the body inclination in the anterior-posterior direction, which is associated with fatigue (Zoppirolli et.al., 2018). Zoppirolli et.al. (2018) found reduced displacement of COM in the forward direction before and during the poling phase due to fatigue, while min zCOM position remained similar. That finding is in contrasts with our findings. These conflicting findings may have to do with a difference in performance level of the participants, with the participants in Zoppriolli et al. (2018) being top 50 finishers the highly popular VSC-race Marcialonga.

In this study, the skiers decreased their peak zCOM at the highest speed (16 km/h), which may reduce their ability to utilize the gravitational force to increase pole force (Zoppirolli et.al., 2015). In the slower speeds, the peak zCOM did not differ to the same extent as min zCOM. The participants are able to maintain the same height of COM before the poling phase, which means that the reduced propulsive force is due to the displacement of min zCOM when fatigued.

4.4 Changes in the hip- and knee joints

Fatigue increased maximum flexion of the hip- and knee joints. Since there was no significant changes in trunk flexion or extension, these results indicate that lowering of the min zCOM-position when fatigued is caused by increased flexion in the hip- and knee joints, which ultimately leads to decreased performance. The results of the present study indicates that peak hip flexion increases at the higher speeds and agrees with the findings of Holmberg et.al. (2006) and Zoppirolli et.al. (2015). In addition to lowered min zCOM position, activation of the hip flexor muscles increases with increasing speed (Holmberg et.al., 2006) and contributes to stiffening of the core and abdominal muscles (Zory et.al., 2009). Despite increased activation of the hip flexors may be beneficial for the performance, increased hip flexion is an indicator of the lowest body position during the poling phase. This may indicate that the participants are not able stiffen the core and abdominal muscles to the same amount. Fatigue is associated with reduced hip flexion during the poling phase (Zory et.al., 2009). According to Holmberg et.al (2005) reduction in hip and trunk flexion during the poling phase could suggest fatigue of the hip flexors muscles (Holmberg et.al., 2005). The results in the present study shows increased hip flexion, with is contradictive to Holmberg et.al. (2005) and Zory et.al. (2009). This may be caused by the extra workload of performing prolonged DP at 6% inclination due to the gravitational force working against the COM, instead of 1% inclinations as in the study of Holmeberg et.al. (2005).

Hip extension is an indicator of the highest position of the hip, which occurs right before pole plant. Increased hip extension can contribute to a higher zCOM, thought which skiers may utilize the gravitational forces to more effective propulsion, which is associated with increased performance (Zory et.al., 2009). Since the participants in this study decreased their hip extension after prolonged DP, their utilization of gravitational forces may not be as beneficial during the fatigued state compared to rested state. Based on the results in this study, the hip ROM increased at the slower speeds when fatigued, which indicates that the hip movement becomes larger.

Based on the results of this study, peak knee flexion angle increases with fatigue. After 2 hours of prolonged DP the participants increased their knee flexion angle, which contributes to the vertical displacement of COM. In this present study, increased knee flexion angle indicates that the participants bend their knees more when they are fatigued than they do in rested state. Decreased knee flexion angle may lead to decreased activation of the legs, which is associated with decreased performance (Holmberg et.al., 2006). The results in present study contradicts this with increased knee flexion angle when fatigued and may be caused by inclination. However, since the peak knee flexion contributes to the displacement of zCOM, the knee joint movement may lead to decreased ability to produce propulsive force (Zoppirolli et.al., 2015).

The ankle ROM was only affected by fatigue at the slowest speed (10 km/h). This indicates that changes zCOM when fatigued did not come from the ankle. However, literature states that the movement in the ankle contributes to a higher zCOM position (Zoppirolli et.al., 2018), and based on the results in this present study, the participants are able to maintain their ankle joint angle when fatigued. Holmberg et.al. (2006) showed that decreased contribution by the hip-, knee- and ankle joints elicited higher blood lactate concentrations due to higher relative load on the muscles producing propulsive forces. Based on these findings and the results of this present study, movements of the knee and ankle joints are of importance in the DP technique. Decreased motion in these joints influences both biomechanical and physiological variables, which decreases the overall performance (Holmberg et.al., 2006).

4.5 Methodological considerations

The results at 10 km/h may not be representative of the participant's normal DP performance. There were several comments from the participants that 10 km/h felt too slow on the treadmill to be relatable to roller skiing outside. More participants are needed to fully understand the effect of fatigue on zCOM position. With more participants, the power of the study increases. Some of the participants in this study reported verbally that they are not used to several hours of prolonged DP, which may have affected the results. Due to the Covid-19 situation, the data collection had to be performed both before as well as after the competitive season. Seasonal changes may therefore have affected the participant's performance due to both physical and psychological factors, such as training status or the prospect/stress of upcoming competitions. The participant's motivation to perform their best may have been lower after the season compared to before the season. Follow-up research on the effect of fatigue on DP kinematics between different groups of skiers, i.e. long-distance skiers compared to all-round skiers, would be beneficial.

5.1 Conclusion

This study investigated the effects of fatigue on prolonged DP on zCOM position and the kinematics of the sagittal joint angles. These results indicated that prolonged DP resulted in fatigue which decreases the performance. Fatigue reduced the zCOM displacement due to more flexed hip- and knee angles. The changes in hip- and knee joints due to fatigue most likely explain the decline in performance after two hours of submaximal DP and demonstrate that fatigue alters the kinematics of DP.

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