Author(s): Ohtonen, Olli; Lindinger, Stefan J.; Göpfert, Caroline; Rapp, Walter; Linnamo, Vesa

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MR OLLI OHTONEN (Orcid ID : 0000-0001-9439-5813)

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Title:

Changes in biomechanics of skiing at maximal velocity caused by simulated 20 km skiing race using V2 skating technique

Running head:

Fatigue induced changes in final spurt

Olli Ohtonen[1*], Stefan J. Lindinger[2], Caroline Göpfert[1,2], Walter Rapp[3] and Vesa Linnamo[1]

[1]Neuromuscular Research Center, Department of Biology of Physical Activity, University of Jyväskylä, Finland.

[2]Department of Sport Science and Kinesiology, University of Salzburg, Austria

[3]Department of Sport and Sport Science, University of Freiburg, Germany

*****Corresponding author:

Tel: +358 50 4077501

E-mail: olli.ohtonen@jyu.fi

ABSTRACT

This study investigated how the fatigue caused by a 20 km simulated skating cross-country skiing race on snow affects the final spurt performance from a biomechanical perspective. Subjects performed a 100 meter maximal skiing trial before and at the end of the simulated race. Cycle characteristics, ground reaction forces from skis and poles, and muscle activity from eight muscles were recorded during each trial.

Results showed that subjects were in a fatigued state after the simulated race manifested by 11.6 % lower skiing speed ($P < 0.01$). The lower skiing speed was related to an 8.0 % decrease in cycle rate ($P < 0.01$) whereas cycle length was slightly decreased (tendency). In temporal patterns relative kick time was increased (10.9 %, $P < 0.01$) while relative poling time was slightly decreased (tendency). Vertical ski force production decreased by 8.3 % while pole force production decreased by 26.0 % (both, $P < 0.01$). Muscle activation was generally decreased in upper (39.2 %) and lower body (30.7 %) (both, $P < 0.01$).

Together these findings show different responses to fatigue in the upper and lower body. In ski forces fatigue was observed via longer force production times while force production levels decreased only slightly. Pole forces showed equal force production times in the fatigued state while force production level decreased threefold compared to the ski forces

Keywords: XC-skiing, force measurements, fatigue

INTRODUCTION

During the last 10 to 15 years there have been changes to the FIS (International Ski Federation) World Cup as well as World Championships and Olympic Games race calendars emphasizing the importance of skiers' abilities to produce high power. Nowadays there is only one race with an interval start in the World Championship and Olympic Games race calendar: 10 and 15 km for ladies and men, respectively, (Kiuru 2016). During the 2015-2016 World Cup season there were only 8 interval start races out of 37 races (Mignery 2015). Other races include sprints (1.2 km to 1.8 km), handicap and mass starts, and team relays where the ability to ski fast several times (man to man fights for positions during the race and in the final spurt) during a race is essential for good results. Even these race forms are different and the fatigue accumulated by repeated sprint and distance events might differ nowadays an extremely good capacity to produce high speeds even in fatigued state is required from the athletes. With this in mind, researchers have recently focused a lot on sprint skiing and have also guided athletes and coaches to concentrate more on the ability to ski fast and to perform strength training, especially for improving upper body capacity (Sandbakk & Holmberg 2014).

Fatigue and the effects of it have been studied quite extensively in XC-skiing. In sprint and distance skiing fatigue has been observed via increased end spurt times in final heats (Mikkola et al. 2013; Vesterinen et al. 2009; Zory et al. 2009), decreased cycle rate (Halonen et al. 2014; Mikkola et al. 2010; Vesterinen et al. 2009), and increased poling time (Halonen et al. 2014; Mikkola et al. 2013) at the end part of the race. In terms of muscle activity (EMG) during sprint skiing, fatigue is showed with lower values in frequency analysis (Zory et al. 2011) between the first and last heat and with lower iEMG values from arms and legs during the end spurt of a simulated sprint race compared to a pre speed test (Vesterinen et al. 2009). Force measurements during sprint and distance skiing simulations are rare, however, Mikkola et al. (2013) reported lower peak vertical and partly horizontal (only last heat) pole force at the end of the sprint heats compared to the start of the sprint heats and Halonen et al. (2014) reported a general decrease in force variables. In distance skiing race analyses cycle length have reported to decrease at the late part of the race while cycle rate remains unaltered (Bilodeau et al. 1996; Rundell & McCarthy 1996; Viitasalo et al. 1997) when using the skating technique.

However, cycle rate and length do not appear to change between the heats in a sprint competition (Mikkola et al. 2010; Vesterinen et al. 2009; Zory et al. 2009). When comparing trials with maximal effort before and after a sprint race simulation decreasing speed is caused by decreasing cycle rate while cycle length remains unaltered (Mikkola et al. 2013; Vesterinen et al. 2009). Studies of the effects of fatigue in final spurt on distance race simulations were not found. In addition to FIS World Cup race distances, fatigue in Marathon skiing (40 km to 90 km) has been reported as decreased MVC and/or EMG amplitude values immediately after the race compared to pre-race values (Boccia et al. 2016; Millet et al. 2003; Viitasalo et al. 1982). An additional reason also for decreased performance with fatigue is compromised coordination, which is observed as unstable movements in the arms and legs that lead to a decrease in speed (Cignetti et al. 2009).

How fatigue is manifested and how it affects XC-skiing is quite well established in sprint skiing in terms of cycle characteristics and muscle activation in addition to possible changes in force production. How fatigue caused by a skating distance race affects athletes' performance and how it is recognized in cycle characteristics, muscle activity, and especially force production remains unanswered and a comprehensive approach with force and EMG measurements is needed. The aim of our study was to find out how the fatigue caused by a 20 km skating race simulation completed by XC-skiing on snow affects the final spurt performance from a kinematic (cycle characteristics), kinetic (ground reaction forces), and muscle activity point of view. Our hypothesis was that maximal performance after the simulated race would be compromised by fatigue resulting from decreased muscle activity (EMG) and force production from lower and upper body leading to decreased cycle time and thus to decreased maximal skiing speed.

MATERIALS AND METHODS

Subjects:

Nine Finnish National level male skiers (28.4 ± 6.3 yr. 74.5 ± 5.7 kg, 176.6 ± 4.5 cm, FIS points 136 ± 42) participated in the study. All of them were informed beforehand about the measurement protocols and they all gave their written consent to participate in the study. All procedures used during the study were preapproved by the ethics committee of the University of Jyväskylä.

Overall design:

Subjects performed a 20 km long XC-ski skating race simulation in the Vuokatti ski tunnel where ambient conditions were constant (temperature: -5° C, air humidity: 85 %) offering equal conditions over the whole measurement period of 5 days. The simulated race was performed as an individual race so that only one subject was racing at the time, skiers were instructed and encouraged to do their best as they would do in real competition. A standard warm up of 15 minutes was performed with moderate training speed (approx. 70 % of max. HR). The race consisted of ten 2 km laps and a total climb (TC) of 45 m per lap totaling 450 m of TC over the whole race. The total climb was approx. two thirds in the current study when compared to world cup tracks TC:s (Ruka 4*5 km, 698 m; Lillehammer 8*2,5 km, 760 m; Toblach 4*5 km, 668 m)(Mignery 2016). To find out how a race affects athletes XC-skiing performance trials with maximal skiing speed were performed before the race (Pre) and during the final spurt at the end of the race (Post). Pre and Post tests were done using the V2 technique (also called as gear 3, G3), where one poling action with both arms is performed for every leg kick on a 100 m long uphill with a gradient of 4°. Both test were done twice and the better trial in both situations, characterized by higher speed, was selected for further analyzes.

Measurement devices

All subjects skied with the same pair of skating skis (Peltonen Supra, Peltonen Ski Oy, Heinola, Finland) prepared with the same wax (Violet Rex Olympic, Oy Redox Ab, Hartola, Finland) and waxing procedures to standardize gliding properties. To measure the ski and pole forces, the skis were equipped with force sensors between the ski and binding (Force binding, Neuromuscular Research Center, University of Jyväskylä) and the poles were equipped with force sensors placed inside the pole handgrip (VELOMAT Messelektronik GmbH, Kamenz, Germany). Force bindings measured forces from vertical and transversal directions. Validity and calibration procedures for the force bindings used in the present study are reported in detail by Ohtonen et al. (2013). The pole force sensor measured axial forces and the calibration of the sensor was conducted by loading the pole equipped with the sensor against a force plate (Neuromuscular Research Center, University of Jyväskylä) with forces approx. equal to forces as measured during V2 skating (approx. 250 N). The pole with the sensor was pressed five times against a force plate in the vertical direction and the values from the force plate and pole force sensor were recorded in order to calculate the appropriate conversion factor from analog voltage response of the pole force sensor to Newtons. All subjects used similar carbon race poles (KV+, Dongio, Switzerland) adjusted to their own normal pole length. Surface EMG was recorded simultaneously with the forces using an EMG suit (Myontec Ltd., Kuopio, Finland). EMG was measured from the following muscles and muscle groups: calf , quadriceps femoris , hamstrings , gluteus , triceps brachii , latissimus dorsi , pectoralis major , and rectus abdominals. The EMG suit has been shown to be a valid measurement device compared to traditional surface electrodes (Finni et al. 2007). All forces and EMG were measured during skiing with the same data acquisition board (sampling rate 1 kHz, NI 9205, National Instruments, Austin, TX, USA) and was thereby synchronized. The data acquisition board was attached to a wireless transmitter (WLS-9163, National Instruments, Austin, TX, USA) and carried by the subject using a waist bag. Data was transferred wirelessly to a PC computer equipped with custom made data collecting software (LabVIEW 2010; National Instruments, Austin, TX, USA). Extra weight caused by the measurement and data collecting equipment totaled 2230 g that was distributed as follows: Force bindings (total left and right) 980 g, pole force sensors (total left and right) 200 g, data collecting and transmitting equipment 1050 g. All trials were also recorded with laser radar (Jenoptik LDM 300 C SPORT, Jena, Germany) to measure the skiers' speed through the measurement station.

Measured and calculated variables

An example of raw force data curves with selected cycle and force variable definitions is presented in Figure 1. Analyzed variables in this study include: skiing speed through the measurement station, cycle time and poling cycle time (defined from right ski/pole contact to subsequent right ski/pole contact) and cycle rate (Hz, defined as cycle time^{-1}) and cycle length (m, defined as product of speed and cycle time). To resolve if there were changes in temporal patterns of the cycle, the cycle time was divided into ground contact time (right ski on snow contact) and leg recovery time (right ski not on snow). Moreover, ground contact time was divided into glide time (from right ski snow contact to force minima prior to the kick) and kick time (force minima during ground contact until the end of ground contact). Unloading phase (from force maximum to minimum during glide) during ground contact is part of the glide time (Figure 1). Poling cycle time was analyzed for temporal patterns by dividing the whole poling cycle time to poling time (time of actual poling action) and poling recovery time (rest of the poling cycle). All temporal patterns of the cycle are presented as percentage of cycle time (%CT). In addition, some variables (ground contact time, kick time, leg recovery time and poling recovery time) are also presented as absolute values. Peak, delta, impulse and average ground reaction force for vertical and transversal directions as well as for axial pole force were calculated (Figure 1). Peak force was defined as highest force during kick for ski forces and the highest active force after impact, caused by the hit of the poles to ground, for pole forces. Delta leg force was calculated only for vertical ski force and is defined as force difference between the force minima during ground contact time and peak vertical ski force (Ohtonen et al. 2016). Impulses for ski and pole forces were defined as area under the force curve during kick time and poling time, respectively. Average forces for ski and pole were calculated over the cycle time for ski forces and poling cycle time for pole forces. All force variables are expressed relative to body weight (%BW). Average rate of force development (RFD) was calculated for vertical ski force and pole force by dividing the delta vertical ski force and peak pole force with time from the beginning of the force development to the peak of force, respectively. Average RFD:s are expressed as N/s. The ratio between pole force and vertical ski force was calculated for peak vertical forces (pole / ski) and average RFD:s (RFD pole / RFD ski) and expressed as the percentage of pole variable from ski variable. The raw EMG signals were band-passed (10-500 Hz) and rectified. The root mean square (rms) for EMG signals was calculated during the kick time for the lower body muscles and during the poling time for upper body muscles. The skiing EMG:s are expressed as percentage of the rms EMG during isometric maximal voluntary contraction (%MVC) conducted separately for all the muscle groups before the skiing measurements. In addition to separate muscle groups an average of normalized lower body and upper body muscle activity were calculated. All skiing variables were calculated over 9 consecutive skiing cycles and averaged.

Data and statistical analyses

All data were analyzed with IkeMaster 1.38a (University of Salzburg, Salzburg, Austria) and Microsoft Office Excel 2010 (Microsoft corporation, Redmond, WA, USA). Statistical analyses were done with PASW Statistics 18 (IBM, Armonk, NY, USA). Differences between Pre and Post skiing test were analyzed with repeated measures ANOVA for skiing speed, cycle variables, forces from skis and poles as well as for EMG:s. Significance level was set to $P < 0.05$.

RESULTS

Average race time in the simulated race was 1:00:33. Maximal skiing speed decreased from 6.13 ± 0.34 m/s to 5.42 ± 0.43 m/s from Pre to Post test representing a decrease of 11.6 % ($P < 0.01$).

Cycle characteristics, ground reaction forces and muscle activities in Pre and Post tests are showed in table 1. Decreased skiing speed was caused by 8.9 % increase in cycle time, ($P < 0.01$) and thus by 8.0 % decrease in cycle rate ($P < 0.01$). Also a tendency of 3.9 % decrease in cycle length ($P < 0.07$) was observed. Absolute ground contact time and kick time increased by 10.5 % and 21.0 %, respectively, (both $P < 0.01$) and absolute leg recovery time showed tendency to increase by 6.1 % ($P = 0.09$) while absolute poling time showed no differences and absolute poling recovery time increased by 9.9 % ($P < 0.01$). Temporal patterns (relative cycle values) showed changes with 10.9 % rise in kick time ($P < 0.01$) and tendencies with 3.4 % and 2.3 % (both, $P < 0.10$) decrease and increase in poling time and poling recovery time, respectively, during Post test.

Ski forces decreased by 8.1 % and 13.4 % in peak vertical ski force and delta vertical ski force (both, $P < 0.01$). Average vertical ski force decreased 12.0 % ($P < 0.01$) while the impulse of vertical ski force increased by 6.1 % ($P < 0.05$). Transversal ski forces (peak, impulse and average) showed a non-significant average change of 7.2 %. Pole forces showed 24.9 %, 19.9 % and 2.6 % lower values in peak, impulse and average forces, correspondingly (all, $P < 0.05$), during Post test. Average rate of force development decreased by 31.2 % and 31.4 % in ski and pole forces, (both, $P < 0.01$). The ratio between peak pole and peak vertical ski force showed a tendency to decrease with 18.5 % ($P = 0.08$). The behavior of the peak vertical ski force and relative kick time as well as peak pole force and relative poling time are presented in figure 2.

Between Pre and Post test lower body muscle activity decreased in calf, quadriceps, hamstrings, gluteus and total average of lower body activity with 25.8 %, 32.5 %, 35.5 %, 25.4 % and 30.7%, correspondingly (all, $P < 0.01$). Similarly in upper body triceps, latissimus dorsi and total average of upper body showed lower muscle activity in Post test by 32.0 %, 56.2 % and 39.2 %, respectively (all, $P < 0.01$). No significant differences were observed between the changes in lower and upper body muscle groups.

DISCUSSION

This study investigated the effects of a 20 km skating race simulation completed by XC-skiing on snow on end spurt performance from a kinematic, kinetic, and muscle activity perspective. Based on the lower speed in the Post test the results suggest that athletes were in fatigued state after the simulated race The fatigue is causing impaired functionality of the muscles which is seen with lower EMG activity causing lower force production and movement frequency. When reflecting our results to the hypotheses, our main findings were that after simulated 20 km ski skating race 1) Cycle rate decreased and cycle length showed a tendency to be diminished. 2) Force production decreased in a different way between pole and ski forces: peak pole force production decreased more compared to peak vertical ski forces. However, while poling time was preserved (and even slightly decreased, tendency), kick time was increased causing a similar decrease in average RFD with arms and legs (Figure 2). 3) EMG activity decreased more with relevant upper body muscle groups contributing to poling compared to lower body muscle groups.

Speed, cycle and force characteristics

Maximal skiing speed measured at the beginning and at the end of the simulated race have reported to decrease 14 % to 16 % (Mikkola et al. 2013; Vesterinen et al. 2009) in sprint skiing using V2 and double poling (DP) techniques, respectively. In distance skiing Halonen et al. (2014) reported 9 % decrease on snow with DP technique. The 12 % decrease in maximal skiing speed observed in this study is comparable with these results. The decrease in speed from a cyclic point of view was caused by a decrease in cycle rate and a minor decrease (tendency) in the cycle length. Vesterinen et al. (2009) noted same phenomenon in sprint skiing with a decrease in cycle rate at the end part of sprint heats, caused by an increase in both absolute poling time and recovery time, as well as with constant cycle length within the heats using V2-technique while roller skiing. Absolute poling recovery time also increased in our study while absolute poling time, in which large individual differences were observed, showed no differences. However, when observing leg patterns we noted an increase in absolute ground contact time and leg recovery time (tendency) indicating that increased cycle time is divided equally into absolute ground contact time and leg recovery time. This indicates that the cyclic pattern changes are different in upper (increase only in absolute pole recovery time, not in poling time) and lower (increase in absolute ground contact time and leg recovery time) body due the fatigue in the current study. Also studies from DP on snow during sprint (Mikkola et al. 2013; Zory et al. 2009) and distance skiing (Halonen et al. 2014) have reported similar changes, but with only in increased poling time with no significant changes in cycle rate. In addition to basic cycle variables this study also focused on clarifying whether there are any changes in the temporal patterns within the cycle manifested by fatigue. In fatigued state athletes demonstrated equal relative ground contact time and recovery time with legs compared to non fatigued state. However, patterns inside the ground contact time changed, glide time showed a tendency to decrease and kick time increased by 11 % (Figure 2. *This highly relevant finding (increase of the kick time) causes 70 % of the increase in cycle time while the duration of the kick time is only approx. 25 % of the cycle time.* This is partly explained by the impaired unloading phase during the ground contact time in the Post test when the skiers are fatigued and was demonstrated by an increase in the difference between peak and delta vertical ski force in Pre and Post tests from 5 % to 15 %. In a recent study from our group (Ohtonen et al. 2016) an increase in relative kick time was observed with high speeds compared to slower speeds indicated that production of a fast push-off phase is critical and could be a discriminating factor between athletes during high speed XC-skiing. This also highlights the importance of this part of the cycle where the push-off of the leg is produced and propulsion is created. However, while the relative kick time was increased when fatigued, the relative poling time was slightly decreased (tendency) (Figure 2) in the present study. This different behavior of the upper and lower body is interesting and indicates different mechanisms for how the upper and lower body reacts to fatigue in cycle characteristics point of view and is also discussed later on force production perspective.

Peak vertical ski forces were slightly higher but still at a rather equal level in our study (1478 N and 1355 N in Pre and Post test, respectively) when compared to earlier V2 studies with direct force measurements showing values from 1299 N to 1414 N (Ohtonen et al. 2013; Ohtonen et al. 2016; Stoggl et al. 2010; Stöggl et al. 2008). On the other hand, peak pole forces were lower in our study (247 N and 188 N, Pre and Post) compared to earlier pole force measurements from V2-technique, which varied approx. 270 N to 300 N (Ohtonen et al. 2016; Smith et al. 2009; Stoggl et al. 2010).

A search of the literature did not reveal studies on XC-skiing (sprint or distance skiing) observing fatigue induced changes in leg forces during skating skiing. In our study peak vertical ski force decreased by 8 % while delta leg force decreased by 13 % indicating, as described earlier, that the unloading was compromised while fatigued. This leads to an increase in the kick time by changing the initial point of the kick to occur earlier in the ground contact phase. This is interesting because the unloading phase, which has been reported to be an important part of the cycle for generating higher forces with the arms and legs, is also linked to performance (Myklebust et al. 2014; Ohtonen et al. 2016). The impulse of the vertical ski force increased by 6 % and this is due to increase in the kick time, not by an increase in force. However, average vertical leg force, which takes into account also the changes in cycle time decreased by 12 % also indicating that the ability to maintain forces is highly compromised after the 20 km simulated race.

While ski forces decreased approx. 10 %, pole forces showed distinctly greater changes varying from 20 % to 26 % in peak, impulse, and average pole force. A decrease in impulse of pole force compared to increase in impulse of vertical leg force demonstrates the different behavior of the lower and upper body with fatigue caused by increasing kick time and slightly decreased (tendency) poling time. Concerning pole forces our results are well in line with Mikkola et al. (2013) studying sprint simulation using DP. They observed a decrease of approx. 20 % to 24 % in peak and average forces between the start and end phases of each heat. However, impulses in their study did not differ whereas we noted decreases of 20 % due to slightly decreased poling time in our study. Halonen et al. (2014) discovered decreases of approx. 14 % in peak forces after a simulated 6 km double poling race. Nonetheless, race time in Halonen et al. (2014) was approx. one third of that in the present study, which might explain the smaller decreases in pole forces. However, in all these cases subjects were instructed to ski as they would do in race situation and thereby the effect of race time should be smaller due to higher intensity during shorter races.

Ratios of peak forces decreased by 19 % from Pre to Post test showing that pole forces decreased more compared to ski forces during this 20 km simulated race, thereby confirming the different response to fatigue with upper and lower body. When combining our results from the changes in cycle characteristics and ground reaction forces we noticed that the changes in average RFD in upper and lower body are rather similar with decreases of approx. 31 % and no changes in the ratio of the RFD:s. This demonstrates that the different mechanisms of fatigue in the upper and lower body cause similar changes in RFD:s of force. In our study pole forces decreased threefold compared to ski forces. Changes in the different fatigability of the upper and lower body have also been reported by Boccia (2016) with non sport specific movements showing greater decreases in fast force production (RFD during MVC) with arms compared to legs (decrease of 26 % with arms while no changes with legs) after classical marathon ski race. As it has been shown earlier in V2-technique arms are contributing two thirds while legs only on third to propulsion force (Smith et al. 2006) which actually propels the skier forward. Propulsion was not measured in this study, but due to changes in the ratio between the arms and legs, fatigue is likely to have some effect on the propulsion distribution generated by arms and legs. However, the decreases in propulsion might be greater than the decreases in just the peak forces of the legs due to compromised coordination and unstable movements (Cignetti et al. 2009) of leg forces when fatigued. This interesting topic with effects of fatigue on propulsion needs further investigation. Transversal forces showed no changes in this study. However, these transversal forces might play an important role when calculating propulsion (Göpfert et al. 2015)

Muscle activity

This study aimed to describe the general effects of fatigue, analyzing whether fatigue was central or peripheral origin was not possible to determine with the methods used in this study. Few actual race analyses have been conducted where EMG:s have been measured before and after the marathon skiing race using isometric MVC in a force dynamometer. Results observed during MVC tests before and after a race showed approx. 30 % decreases in EMG activity (Millet et al. 2003; Viitasalo et al. 1982) with leg muscles, which are comparable to our results. Also a recent study shoved smaller changes after marathon race with 10 % (elbow) to 20 % (knee) decreases (Boccia et al. 2016). In our study, the latissimus dorsi muscle showed the highest relative values (150 %) compared to MVC in Pre test. This result is in agreement with Halonen et al. (2014) highlighting the importance of this muscle during poling action in V2 skating as well as DP where the poling action is rather similar. Our study also noted the greatest decreases due to fatigue (over 50 %) in this muscle, which is highly relevant during the whole push-off phase. The importance of the latissimus dorsi, pectoralis and teres major (not investigated in this study) muscles to double poling action have been shown by Holmberg et al. (2005) and Lindinger et al. (2009). The pectoralis muscle showed the second highest decrease with 36 % (tendency) in our study. Compromised muscle activity due to fatigue in these highly important muscles contributing to poling action of double poling and V2 is likely causing a less stable push-off action during poling and the force might "leak" out due the "softness" of these muscles. As showed earlier, pole forces in V2 technique are partly generated by lifting the center of mass (COM) into a high position with the legs and then "dropping" the body mass onto the poles while the torso and arms must form a stable frame so that the force is transmitted to the poles (Myklebust et al. 2014; Ohtonen et al. 2016). This also highlights the importance of the latissimus dorsi, pectoralis and triceps brachii muscles. Therefore, if the stability of these muscles is compromised the force is not likely optimally transferred to the poles. The decrease in the EMG activity of the latissimus dorsi muscle among other muscles in the upper body is probably linked to a greater decrease in pole forces where upper body EMG decreased by 39 % compared to ski forces whereas lower body EMG decreased by 31 %. Still there was no statistical difference between the changes in upper and lower body in fatigued state. However, Vesterinen et al. (2009) did not notice changes in latissimus dorsi muscle in a simulated sprint race. Nonetheless, they found a decrease of approx. 18 % in sum iEMG from triceps brachii and vastus lateralis representing a general EMG for the whole body, which is smaller compared to ours.

PERSPECTIVE

20 km skating XC-skiing causes fatigue, which is observed as decreasing speed after a race. This reduction in speed is caused by decreased EMG activity, which leads to compromised force production and decreased movement frequency. Different kinds of fatigue-induced responses are observed with the lower and upper body: kick time is increased while poling time is preserved and pole forces are decreased threefold in comparison to ski forces (Figure 2). Increased kick time is caused partly by an impaired ability to use unloading prior the kick. Greatly decreased pole forces are due to a compromised ability to maintain a stable upper body.

Practical implications for coaches and athletes based on this study are to perform technique training sessions in a fatigued state and with high speeds to create adaptations and stabilize technique. Special focus should be put on to achieve total unloading to maximize rapid force production during kick phase as well as to maintain rigid upper body position during poling to minimize pole force reduction when fatigued.

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Table 1. Kinematic, kinetic and muscle activity variables from Pre and Post measurements and differences between them. Significance is determined between Pre and Post measurements

Variable	**Unit**	**Pre**	**Post**	**Difference (%)**
Cycle characteristics				
Cycle time	[s]	1.41 ± 0.06	1.53 ± 0.07	8.9 ± 4.7**
Cycle rate	[Hz]	0.71 ± 0.03	0.65 ± 0.03	-8.0 ± 4.2**
Cycle length	[m]	8.64 ± 0.61	8.30 ± 0.73	-3.9 ± 5.4$^{\#}$
Ground contact time, relative	[%CT]	60.25 ± 1.92	61.21 ± 3.93	1.5 ± 3.9
Ground contact time, absolute	[s]	0.85 ± 0.04	0.94 ± 0.08	10.5 ± 6.2**
Glide time, relative	[%CT]	35.17 ± 2.20	33.41 ± 2.85	-4.9 ± 6.7$^{\#}$
Kick time, relative	[%CT]	25.09 ± 1.69	27.79 ± 2.05	10.9 ± 6.2**
Kick time, absolute	[s]	0.35 ± 0.03	0.43 ± 0.04	21.0 ± 9.9**
Leg recovery time, relative	[%CT]	39.75 ± 1.92	38.79 ± 3.93	-2.6 ± 6.8
Leg recovery time, absolute	[s]	0.56 ± 0.04	0.59 ± 0.05	6.1 ± 8.9$^{\#}$
Poling time, relative	[%CT]	38.59 ± 3.98	37.20 ± 3.97	-3.6 ± 4.9$^{\#}$
Poling recovery time, relative	[%CT]	61.41 ± 3.98	62.80 ± 3.98	2.3 ± 3.0$^{\#}$
Poling recovery time, absolute	[s]	0.44 ± 0.04	0.48 ± 0.04	9.9 ± 6.1**
Ground reaction forces				
Peak vertical ski force	[%BW]	202.48 ± 10.28	185.99 ± 20.51	-8.3 ± 6.9**
Delta vertical ski force	[%BW]	197.00 ± 10.44	170.82 ± 23.91	-13.4 ± 9.8**
Impulse of vertical ski force	[%BW]	42.26 ± 2.60	44.73 ± 1.92	6.1 ± 5.4*
Average of vertical ski force	[%BW]	119.87 ± 8.13	105.44 ± 8.53	-12.0 ± 4.6**
RFD of vertical ski force	[N/s]	6859 ± 1046	4685 ± 1155	-31.2 ±16.0**
Peak pole force	[%BW]	35.9 ± 4.40	26.03 ± 6.42	-24.9 ± 17.4*
Impulse of pole force	[%BW]	5.30 ± 0.70	4.40 ± 1.09	-19.9 ± 17.6*
Average of pole force	[%BW]	19.47 ± 2.39	15.46 ± 3.16	-22.6 ± 2.9*
RFD of pole force	[N/s]	2198 ± 391	1532 ± 300	-31.4 ± 16.6**
Peak pole force / Peak vertical ski force	[%]	16.79 ± 2.42	14.00 ± 3.90	-18.5 ±19.1$^{\#}$
RFD pole / RFD ski	[%]	33.27 ± 7.01	35.56 ± 14.63	1.46 ± 28.0

Muscle activity				
Calf	[%MVC]	98.5 ± 38.2	72.9 ± 27.7	-25.8 ± 16.1**
Quadriceps	[%MVC]	115.2 ± 36.0	78.9 ± 30.9	-32.5 ± 10.1**
Hamstrings	[%MVC]	104.4 ± 44.6	70.8 ± 41.5	-35.5 ± 16.5**
Gluteus	[%MVC]	75.9 ± 40.6	55.5 ± 26.2	-25.4 ± 10.3**
Lower body	[%MVC]	98.5 ± 27.3	69.5 ± 24.2	-30.7 ± 11.2**
Triceps	[%MVC]	112.3 ± 57.7	72.9 ± 32.0	-32.0 ± 9.4**
Latissimus dorsi	[%MVC]	154.2 ± 45.3	63.3 ± 20.7	-56.2 ± 6.5**
Pectoralis	[%MVC]	135.6 ± 131.6	64.8 ± 51.3	-38.1 ± 21.5$^{\#}$
Abdominal	[%MVC]	98.6 ± 36.2	87.0 ± 44.2	-11.8 ± 22.5
Upper body	[%MVC]	123.8 ± 38.3	72.0 ± 19.1	-39.2 ± 9.7**

Data are presented as the mean ± SD.
Significance is determined with ANOVA
= P < 0.10, * = P < 0.05, ** = P < 0.01, different to Pre test
RFD of vertical ski force, average rate of vertical ski force development; RFD of pole force, average rate of pole force development; Peak pole force / Peak vertical ski force, ratio between peak pole force and vertical ski force; RFD pole / RFD ski, ratio between average rate of pole force development and average rate of vertical ski force development; s, second; Hz, Herz, s^{-1}; m, meter; %CT, percent of the cycle time; %BW, percent of the body weight; %MVC, percent of the maximal voluntary contraction.

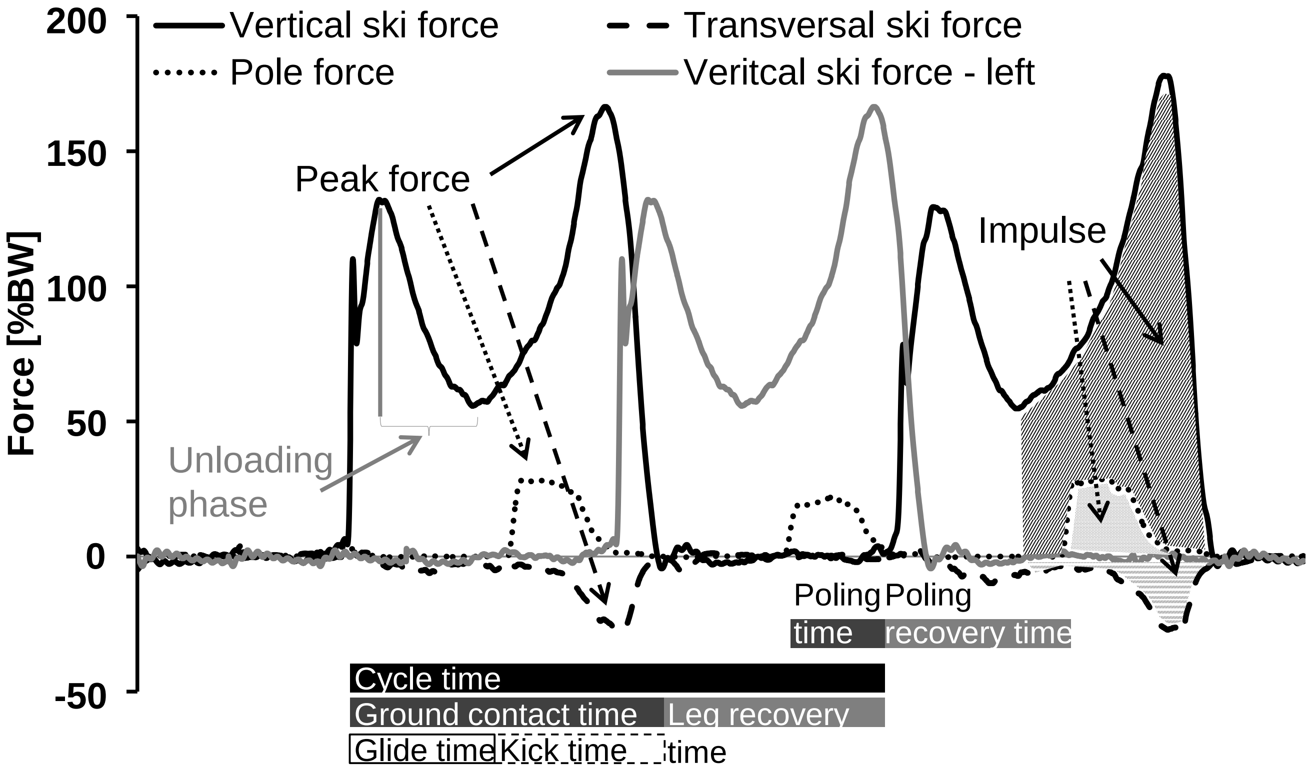

Figure 1. Example figure of the raw data with cycle and force variable definitions.

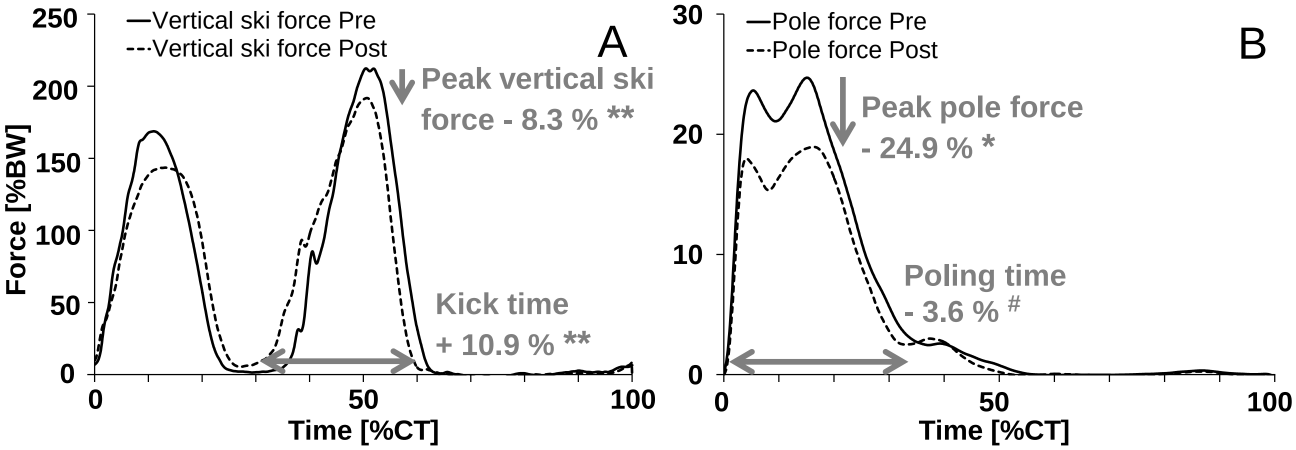

Figure 2. Ski (A) and pole (B) force curves averaged over nine cycles from one representative subject. Mean changes from all subjects between Pre and Post test are presented for Kick time and Peak vertical ski force as well as for Poling time and Peak pole force for showing the different behavior of the ski and pole forces when fatigued. $^{\#}$, $P < 0.10$; *, $P < 0.05$; **, $P < 0.01$.