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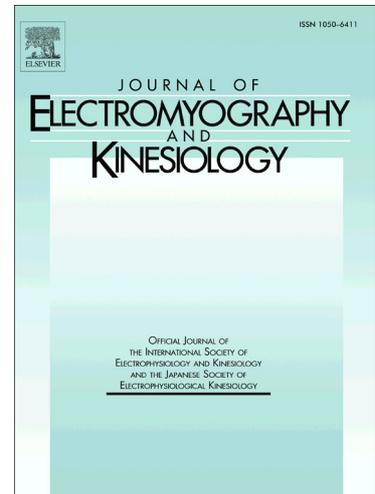
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Biomechanics of simulated versus natural cross-country sit skiing

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Abstract

The purpose of this study was to investigate the biomechanics of cross-country sit-skiing in simulated and natural skiing. Thirteen international level athletes participated in a ski ergometer test (simulated conditions) and a test on snow in a ski-tunnel (natural conditions) using their personal sit-ski. Tests in both conditions were performed at individual maximal speed. When comparing the two conditions the main results were: 1) maximal speed in simulated conditions was lower ($p < 0.05$) but correlated well with the natural condition ($r = 0.79$, $p < 0.001$); 2) no differences in pole force variables were found; peak force ($r = 0.77$, $p < 0.01$) and average force ($r = 0.78$, $p < 0.01$) correlated well; 3) recovery time and time to peak did not differ and time to impact correlated with each other ($r = 0.88$, $p < 0.01$); 4) no differences were found in peak electromyography (EMG) and average EMG for Triceps, Pectoralis, and Erector Spinae; Rectus Abdominis did not differ in peak. EMG peak and average EMG of all muscles were correlated between the two conditions ($r = 0.65$ – 0.94 ; $p < 0.05$ – 0.01). Although some differences were observed, this study demonstrated that technical skill proficiency in natural and simulated cross-country skiing is comparable from a force production and muscle activation perspective.

Introduction

Since the first Paralympic cross-country (XC) skiing event, the number of athletes who practice this discipline has grown markedly while live television broadcasting and print media attention have also increased (Rombach and Rapp 2014). Paralympic athletes with neuromusculoskeletal impairments are divided in two categories: standing and sitting. To ensure equal and fair competitions and to minimize the effects of impairment on performance within each category, athletes are divided into classes according to the impact of neuromusculoskeletal impairment on XC-skiing performance (Vanlandewijck 2006; Tweedy and Vanlandewijck 2011; International Paralympic Committee 2015). All sit-skiers have impairment in the lower limbs, but a different level of ability to control the trunk. Therefore, sit-skiers are grouped in five different classes LW (locomotor winter), from LW12 (athletes can perfectly control their trunk muscles) to LW10 (athletes with no voluntary abdominal and trunk extensor control), with three intermediate categories: LW11.5, LW11 and LW10.5 (International Paralympic Committee 2015). Independent of the impairment level, all sit-skiers adopt the double poling (DP) technique for propulsion. DP is a technique in which athletes sitting on a sledge mounted on a couple of cross-country skis, sit-ski, generate propulsion by using shoulder and arm muscles to push on two poles synchronously; the propulsion is increased by a flexion-extension movement in the trunk.

Although many studies have been conducted on the physiology (Hoffmann et al. 1991; Pellegrini et al. 2013), biomechanics (Millet et al. 1998a, 1998b; Holmberg et al. 2005, 2006; Stöggl and Holmberg 2011; Zoppirolli et al. 2015), and neuromuscular activity (Holmberg et al. 2005) of able-bodied skiers in DP, very few studies have assessed this technique in sit-skiing. Bernardi et al. (2013) evaluated changes in speed and kinematic parameters during flat and uphill tracks, finding an average cycle duration of 0.98 s and 0.84 s respectively, while Gastaldi et al. (2012, 2014, 2016), investigated DP kinematics in sit-skiing athletes belonging

to different classes using a markerless kinematic analysis. In the comparison of DP technique of different classes (LW10 and LW11) it was demonstrated that athletes kneeling on the sit-ski (kneeling position) and athletes sitting on the sit-ski with the knees in a higher position relative to the hip joints (knee-high position) had significantly different trunk movement (Gastaldi et al. 2012). Finally, the trunk movement was assessed in simulated skiing among athletes with different impairments, demonstrating that athletes with a lower impairment level had a greater range of motion (ROM) and a more flexed trunk position during the DP cycle than athletes with a higher impairment level (Rosso et al. 2016).

Studies on DP sit-skiing (Gastaldi et al. 2012; Bernardi et al. 2013) showed that conducting tests skiing on snow (natural conditions) can be challenging in providing precise and comparable results due to the environmental constrictions; therefore it is necessary to introduce standardized test procedures for valid assessment and training. Such test procedures can be conducted in a laboratory, which guarantees standardization, easy access to the athlete, and less technological challenges. In able-bodied athletes laboratory tests on an ergometer (simulated conditions) have been conducted to evaluate if testing and training simulating DP technique gives accurate and valid results and comparable movements in terms of muscle recruitment and forces (Holmberg and Nilsson 2008; Halonen et al. 2014). Although Halonen et al. (2014) found a difference in abdominal muscle activation time between simulated and natural conditions, a strong correlation was found in power generation during a six-minute test (Holmberg and Nilsson 2008), in force production and muscle activities, and in impact of fatigue (Halonen et al. 2014). Comparison between simulated and natural conditions has also been done in XC sit-skiing. Forbes et al. (2010) compared aerobic response measuring cardiorespiratory variables, such as peak oxygen consumption (VO_{2peak}), peak heart rate, peak respiratory exchange ratio, and anaerobic response measuring blood lactate. Forbes et al. (2010) reported no differences in VO_2 , but higher values in all other variables in simulated

compared to natural conditions. Other studies have used simulated conditions to describe sit-skiers' physical fitness and consequently give advice on training and performance (Bernardi et al. 2010, 2012; Bernardi and Schena 2011). An arm cranking ergometer was used to assess both aerobic and anaerobic responses showing high values for VO_{2peak} , heart rate, and blood lactate (Bernardi et al. 2010; Bernardi and Schena 2011), while upper body muscular strength was identified as a key factor for both aerobic and anaerobic capacity (Bernardi et al. 2012). VO_{2peak} -values as a result of incremental maximal cardiopulmonary arm-cranking, present a close relationship with VO_2 measured during a 5 km simulated race (Bernardi et al. 2010).

The aim of this paper is to compare force generation and muscle activity patterns in sit-ski athletes using an XC-ergometer versus natural conditions on snow. It would permit to consider if XC-ergometer is a valid alternative for specific training, to improve XC sit-skiing performance in natural conditions.

Methods

Participants

Thirteen healthy elite Paralympic XC sit-skiers (8 male, members of seven different National teams; representing different classes LW10 n=1, LW10.5 n=1, LW11 n=3, LW11.5 n=4, LW12 n=4; age 27 ± 3 years (20-33), height 167 ± 20 cm (110-192), weight 58 ± 12 kg (30-79)) volunteered as participants. Participants were informed in full detail about the aim and the nature of the study and they signed an informed consent. The research methods and the protocols were standard and have been approved by the Ethics Committee of the University of Jyväskylä and the measurements were performed in accordance with the Declaration of Helsinki.

Overall design and experimental setup

All the tests were conducted during the International Paralympic Committee (IPC) World Cup in December 2014 in Vuokatti, Finland. The protocol consisted of two parts: the first part took place in a laboratory, while the second part was conducted in the Vuokatti Ski Tunnel. The athlete was prepared for testing and practiced with the XC-ergometer (Concept2 Inc, Morrisville, Vermont, USA) for 5 to 10 minutes to warm up and to become familiar with the equipment. All the athletes used the same ergometer but with their own sit-ski. For each athlete, the sit-ski was fixed with respect to the ergometer at the distance that allowed the skier to have technique as similar as possible to the one usually used in natural condition. The XC-ergometer (Figure 1) was fixed to the wall in a vertical position; this setup allowed the athletes to activate the flywheel by pulling the ropes using two handles. The ergometer resistance was set at 7.5 out of 10 (arbitrary units) for all participants; this level was chosen based on pilot tests to best simulate natural skiing conditions in the Vuokatti Ski Tunnel. Two maximal speed ($speed_{max}$) trials were performed and separated by 2 minutes of recovery. The athletes were requested to execute at least 7 cycles after $speed_{max}$ was reached. As a consequence, each trial lasted no longer than 15 s. The best trial at $speed_{max}$ (characterized as the fastest) was selected and analyzed. The $speed_{max}$ condition was chosen because of its importance in race strategies. It has been demonstrated (Bernardi et al. 2012) that in races sit-skiers adopt the “all out” strategy in which athletes start with a high speed and that this subsequently decreases during the race.

For the second part of the experiment, the athlete was transferred to the Vuokatti Ski Tunnel (constant temperature of -7° and humidity condition). The sit-ski was the same used in the laboratory test (personal sit-ski) and poles equipped with force transducers were provided to skiers (lengths from 100-130 cm at 2.5 cm increments). The skis were prepared by the athletes' own ski service team before the measurements started. The track profile was chosen to be 16 m long at 2.5° of slope and was also selected based on pilot tests. Two $speed_{max}$ tests

with a recovery of 2 min in between were performed; the fastest was selected for further analysis.

Maximal speed

In simulated conditions the maximal speed was calculated by using data recorded by the ergometer software. The ergometer gave a value, which is the time required to cover a distance of 500 m if the speed the athlete has in that moment will be maintained. The maximal speed was the ratio between the theoretical distance of 500 m and the time given by the ergometer. In natural conditions the speed was measured with radar (Jenoptik LDM 300 C SPORT, Jena, Germany).

Force and cycle characteristics measurements

In simulated conditions, the ergometer was equipped with force transducers (University of Jyväskylä, Finland) mounted between the pulling rope and handle grip. Pulling forces were collected at 3000 Hz by Vicon Nexus software (Vicon Motion Systems Ltd. UK). In natural conditions poles were equipped with a strain gauge force transducer mounted directly in the pole grip (University of Salzburg, Austria). Force data were collected at 1000 Hz using a custom-made data collection system explained in a previous study (Halonen et al. 2014).

In Figure 2 cycle characteristics and poling forces are presented for both simulated and natural conditions. Cycle time (CT), poling time (PT), and recovery time (RT) were the duration of the DP cycle, poling phase (PP), and recovery phase (RP) respectively. The impact force ($force_{\text{impact}}$) occurred at the impact of the pole to the ground and was characterized as the first force peak occurring during the PP; the peak force ($force_{\text{peak}}$) is related to propulsion and was determined as the highest active peak force after the impact during the PP (Figure 2). The other force variables calculated were average force ($force_{\text{avg}}$) and integral force ($force_{\text{int}}$), while the cycle characteristics variables were time to impact (TtI) and time to peak (TtP). TtI and TtP were defined as the time between the beginning of the PP

and the time when the $force_{impact}$ and $force_{peak}$ occurred, respectively. All biomechanical variables were calculated for each of seven consecutive propulsion cycles in the same manner in both simulated and natural conditions.

Muscle activity measurements

Muscle activity was acquired by a surface electromyographical system that transmitted the data wirelessly (TeleMyo DTS, Noraxon U.S.A. Inc, United States) to a personal computer and was stored by Vicon Nexus software. The TeleMyo DTS system is composed of sensors system, which include a small amplifier, and a belt transmitter, to transmit data from the sensors to a synchronization station and then to a personal computer by a USB connection. The system applied a pass-band filter (20-400 Hz) and converted analog signals to digital data by a 16-bit A/D converter. In simulated conditions signals were sampled at 3000 Hz and synchronized with force data. In natural conditions a sample frequency of 1500 Hz was used. Moreover, the Triceps (Tric) activity was registered at 1000 Hz by the custom-made system used to collect pole forces. This double acquisition was used to manually synchronize forces and muscle activity signals from the two acquisition systems.

Muscle activity signals were recorded in a single differential configuration using pre-gelled Ag/AgCl bipolar surface electrodes (circle shape, sensor area 28 mm²) with an inter-electrode distance of 15 mm (Ambu BlueSensor N, Ambu A/S, Denmark). The electrodes were positioned according to SENIAM recommendation (Hermens et al. 2000) on the most prominent muscle belly in the line of the muscle fiber direction, and were placed over 8 muscles: Tric, Pectoralis Major (Pec), Latissimus Dorsi (Lat), Rectus Abdominis (RecAb), Obliquus Abdominis, Erector Spinae (ES), Rectus Femoris and Biceps Femoris muscles of the right side of the body. A reference electrode was placed on the right acromion. Before electrode positioning, the skin was abraded and cleaned with alcohol. Since for the majority of the participants the activity of Obliquus Abdominis, Rectus Femoris and Biceps Femoris

was low, these muscles were not taken into account in final analysis. The low activation was justified by the individuals' impairment and their lack in trunk and lower limb muscle control.

Raw muscle activity signals were full-wave rectified and 10 Hz low pass filtered to create a linear envelope. For each cycle the average muscle activity (aEMG) and the muscle activity peak (EMG_{peak}) were calculated on the rectified signals and on the linear envelope respectively (Holmberg et al. 2005). Since the minimum number of good cycles available for all the athletes was lower than seven, neuromuscular variables were calculated from five out of seven consecutive propulsion cycles. To analyze coordination patterns, an electromechanical delay was evaluated as a difference between two time instances. During each PP both muscle activity and force signals increased from and then decreased to a baseline value. The muscle activity and force onset corresponded to the time instant when increasing signals reached 10% of their maximum. The difference between muscle activity onset and force onset is generally defined as onset delay. The offset delay was calculated in the same way when the muscle activity and force signals decreased. The onset and offset delay was reported negative when the muscle activation occurred before the force, both in terms of activation and deactivation. A ratio between natural and simulated conditions for muscle activity variables has been calculated to compare muscle activation levels in different conditions (Pellegrini et al. 2005).

The force, cycle characteristics, and neuromuscular data were processed using custom-made code prepared in MatLab (MatLab and Release 2015, The MathWorks, Inc., Natick, Massachusetts, United States).

Statistics

Since the data did not show a normal distribution (Kolmogorov-Smirnov test; $p < 0.01$) non-parametric statistics was applied. Data was presented as mean and standard deviation and median \pm interquartile range (IQR) in the tables. To check for statistical differences between

the two conditions, a Wilcoxon test was applied and a pairwise comparison using Spearman correlation coefficient (r) was calculated for each variable. Statistical significance was set at $p < 0.05$ for all analyses. All statistical analyses were processed using MatLab.

Results

Speed_{max} values, forces and cycle characteristics in natural and simulated conditions were reported as mean \pm SD and median \pm IQR in table 1. Speed_{max} in natural conditions was higher ($p < 0.05$) than in simulated conditions. A positive significant correlation was found between simulated and natural skiing ($r = 0.79$, $p < 0.001$).

No differences were found between simulated and natural conditions in the force_{impact}, force_{peak}, force_{avg}, RT, and TtP. In contrast, in simulated conditions the force_{int} ($p < 0.001$), the CT ($p < 0.001$), the PT ($p < 0.001$), and the TtI ($p < 0.01$) were higher compared to the natural conditions. A positive significant correlation was found between simulated and natural conditions in force_{peak} ($r = 0.77$, $p < 0.01$), force_{avg} ($r = 0.78$, $p < 0.01$), and TtI ($r = 0.88$, $p < 0.01$).

Muscle activation values were reported as mean \pm SD and median \pm IQR of the ratio natural/simulated in the table 2, while muscle activation onset and offset delay in the two conditions were reported as mean \pm SD in figure 3.

Concerning the muscle activation, no differences were found between simulated and natural conditions in the EMG_{peak} and aEMG for Tric, Pec, ES, and in EMG_{peak} for RecAb. In contrast, higher activation was found in simulated compared to natural conditions in EMG_{peak} for Lat ($p < 0.05$), in aEMG for Lat ($p < 0.05$) and RecAb ($p < 0.05$). Concerning the onset delay (Figure 3A), Tric ($p < 0.001$), Pec ($p < 0.001$), Lat ($p < 0.001$), and ES ($p < 0.05$) were activated later in simulated than in natural conditions. Regarding the offset time (Figure 3B), Tric ($p < 0.05$) and Lat ($p < 0.01$) were deactivated later in simulated than in natural conditions.

A positive significant correlation was found between simulated and natural conditions for all muscles in EMG_{peak} Tric ($r = 0.69$, $p < 0.01$), Pec ($r = 0.88$, $p < 0.01$), Lat ($r = 0.94$, $p < 0.01$), ES

($r=0.77$, $p<0.05$), RecAb ($r=0.78$, $p<0.01$) and aEMG Tric ($r=0.69$, $p<0.05$), Pec ($r=0.77$, $p<0.01$), Lat ($r=0.80$, $p<0.01$), ES ($r=0.65$, $p<0.05$), RecAb ($r=0.75$, $p<0.01$).

Discussion

The present study aimed to compare force generation, cycle characteristics, and muscular activity of XC sit-skiers during simulated and natural conditions and showed that activity patterns of the major trunk and arm muscles during simulated XC-skiing on an ergometer mirrored natural XC-skiing well.

Comparing the two conditions, maximal speed was significantly lower using the ski ergometer than in the tunnel. Nevertheless, the positive correlation found between the two conditions means that athletes skiing faster on the snow were able to obtain better performances also in simulated conditions. Mean speed values obtained in the current study in natural conditions are higher compared to the speed measured during the first lap of a race in a previous study (Bernardi et al. 2013); a lower slope (2.5° vs 8.3°) and a shorter time of effort in the present study might explain these differences.

Force is generated differently in simulated conditions (traction force) and natural conditions (pushing force), thus comparing the muscle activity pattern and the biomechanical responses in both conditions may be influenced. A large treadmill would probably be closer to natural skiing than a simulation on the ski ergometer, but a ski ergometer is more accessible for many athletes to be used in training. One fundamental question of the present study was to compare generated forces in these two conditions and, despite the obvious differences, the forces measured were quite similar. If the main aim was to compare joint kinematics, a treadmill would have been preferred.

Forces generated showed two peaks per each DP cycle (Figure 2). The first peak occurred at the impact, while the second is related to propulsion. Compared to able-bodied athletes who showed lower impact force with respect to peak force (Holmberg et al. 2005),

XC sit-skiers impact force was higher in both conditions. This higher impact force may be due to the sitting position and the ability of the athlete to take advantage of the force of gravity when poling, which influences the inclination of the pole at ground contact and subsequently the force transmitted to the ground at the impact through each pole. However, to verify this assumption, the direction of the force application should be measured. The impact force induced a pre-activation of Pectoralis and Rectus Abdominis (Figure 3A) to increase the muscle stiffness in order to prepare the body for the pole impact, and stabilizes the involved joints to generate more propulsion at the beginning of the poling phase similar to able-bodied skiers (Holmberg et al. 2005).

At maximal speed, the cycle time and the poling time were longer for athletes skiing in simulated conditions compared to natural conditions, while the recovery time was similar between the two conditions, which is in agreement with previous studies in able-bodied skiers (Pellegrini et al. 2005; Halonen et al. 2014). Moreover, the longer poling time leading to higher integral force during the poling phase is in line with a previous study conducted in able-bodied skiers as well (Halonen et al. 2014). The difference in the cycle time and poling time might be due to the higher resistance in simulated conditions indicated by lower speed and/or to different kinematics of the upper arms (traction force), which might lead to a greater elbow and shoulder range of motion during the poling phase. More specifically, it could be that in the simulated conditions at the end of the recovery phase athletes' wrists are in a more elevated position and the elbow joint angles are more extended than in natural conditions because of the elastic return force generated by the elastic mechanism inside the flywheel bringing the arms forward during the recovery phase. As a result, the first part of elbow flexion in the propulsion phase might be similar to a pull-up movement (Stöggl et al. 2006). This greater range of motion in the upper limbs could also explain the higher peak and average muscle activity for Latissimus during the poling phases in simulated compared to the

natural conditions because of its extensor function in the first part of the poling phase (Holmberg et al. 2005). Moreover, a greater trunk flexion in simulated conditions during the poling phase could explain the higher Rectus Abdominis activation, which indicates better stability.

Concerning the onset and offset delay the high variability shown especially in abdominal muscles (Rectus Abdominis and Erector Spinae) can be due to the different classes of athletes included in this study. The decision to consider all the classes in the current sit-ski classification in the present study was because of the possibility to extend results to all sit-skiers and the low number of athletes per each class. Statistical analysis on onset delay revealed later activation for Triceps, Pectoralis, Latissimus, and Erector Spinae in simulated compared to natural conditions. This could be due to the advantage in raising the upper limbs that athletes get from the elastic return force generated by the ergometer's flywheel during the recovery phase, while in natural conditions skiers must raise their upper limbs voluntarily. In contrast, the lack in difference for Rectus Abdominis onset delay is in contrast with the behavior showed by able-bodied athletes activating the Rectus Abdominis 0.1 s earlier using the ergometer compared to skiing on snow (Halonen et al. 2014). Despite this difference in activation time, the upper limb extensor muscle activation order is similar between simulated and natural conditions. This similarity suggests that in both conditions the gesture involves first a push (Triceps and Pectoralis) and then a pull (Latissimus and Erector Spinae) action, even though skiing on the ergometer athletes pull a rope while skiing on snow they push a couple of poles (Figure 3A). The offset delay showed a later deactivation of Triceps and Latissimus in simulated compared to natural conditions, which could be explained by the supposed greater upper limbs range of motion during the poling phase.

Despite these differences in Latissimus and Rectus Abdominis activity and the longer cycle and poling time, high correlations were found in the peak and average values of muscle

activity for all muscles, in time to impact, peak force, and average force. These high correlations suggest that on the XC ergometer athletes who had higher absolute muscle activity and generated force in simulated conditions reacted the similarly in natural conditions.

To sum up, similar muscular activity in Triceps, Latissimus, and Erector Spinae muscles, activation pattern for Triceps, Pectoralis, Latissimus, Erector Spinae, and Rectus Abdominis muscles, and level of force generated were observed between natural and simulated conditions, while simulated condition had longer poling and cycle time and higher integral force. This comparable muscular activity, together with the similar pattern of activation and generated force in natural and simulated conditions suggest that the XC-ergometer is a good device for training specific upper body maximal strength and testing aerobic and anaerobic capacity in sport-specific reliable and repeatable conditions. In contrast it might be that endurance training has negative effect on the technique due to the different upper limbs and trunk kinematics (Stöggl et al. 2006), but additional study focusing on motion analysis should be done.

Limitations

In the present study there are three main limitations. The first limitation is the small sample size. It would be important to get a representative number of athletes from each class, but this is difficult due to the low number of elite athletes competing in XC-sit skiing. The second is the lack of a kinematic analysis to evaluate trunk and upper limb angles and ROM, which allow only speculation regarding the possible explanations for the statistical differences found in time variables and muscle activation. The third is the lack of analysis in force directions that compared to sit-ski kinematics could give a reasonable explanation for the differences between standing able-bodied and sit-skiers in the impact force and peak force values and for

the opposite order of activation in shoulder extensors. Indeed, athletes with strong trunk impairment try to compensate by changing their DP technique.

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Figure caption:

Figure 1. Laboratory setup used for simulated skiing. A XC-ergometer allowed athletes to simulate the skiing gesture by means of a mechanical system of ropes and pulleys. A force transducer is inserted between each rope-handle grip coupling to collect force data and to evaluate cycle characteristics. Athletes performed the simulated skiing using their personal sit-ski and skies. The sit-ski was fixed with respect to the XC-ergometer at an adequate distance to allow the athletes to better simulate the gesture they demonstrated during natural skiing.

Figure 2. Force and cycle characteristics in the two conditions. A. This figure shows two of the force variables, impact force ($force_{impact}$) and peak force ($force_{peak}$), and three cycle characteristics variables, cycle time (CT), poling time (PT), and recovery time (RT), for simulated conditions. The $force_{impact}$ was characterized as the first force peak which occurred during the poling phase, while the $force_{peak}$ was determined as the highest active peak force after the impact during the poling phase. The CT measured the double poling duration in seconds; the PT was the period of time which began when the force started to grow sharply with respect to the baseline value and ended when the force came down to the initial value; the RT was the mathematical difference between the CT and PT. B. The same force and cycle characteristics are shown in natural.

Figure 3. Onset and offset delay. The figure reported onset delay (Figure 3A) and offset delay (Figure 3B) for the five muscles (Tric, Pec, Lat, ES, RecAb) as mean \pm SD. This delay is calculated considering a threshold of 10% of the muscular activity and force peak. Statistical difference between the two conditions are reported, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

Acronym list

CT = cycle time

EMG = electromyography

aEMG = average muscle activity

EMG_{peak} = muscle activity peak

ES = Erector Spinae muscle

DP = double poling

force_{avg} = average force during poling phase

force_{impact} = force at the impact

force_{peak} = peak of force in the poling phase

force_{int} = integral of force during poling phase

IPC = International Paralympic Committee

IQR = interquartile range

Lat = Latissimus Dorsi muscle

LW = locomotor winter

Pec = Pectoralis Major muscle

PP = poling phase

PT = poling time

RP = recovery phase

RT = recovery time

SD = standard deviation

Speed_{max} = maximal speed

TtP = time to peak

TtI = time to impact

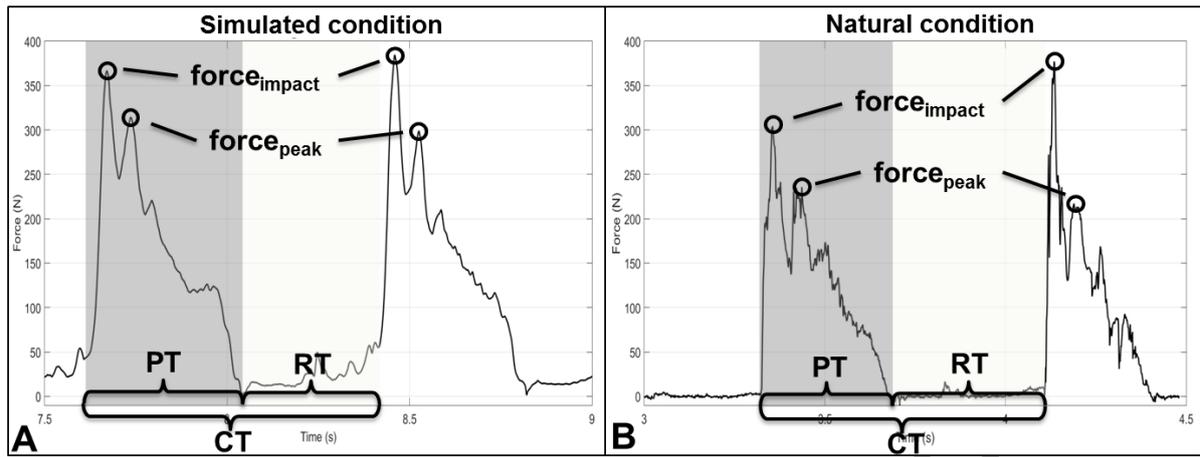
Tric = Triceps Brachii muscle

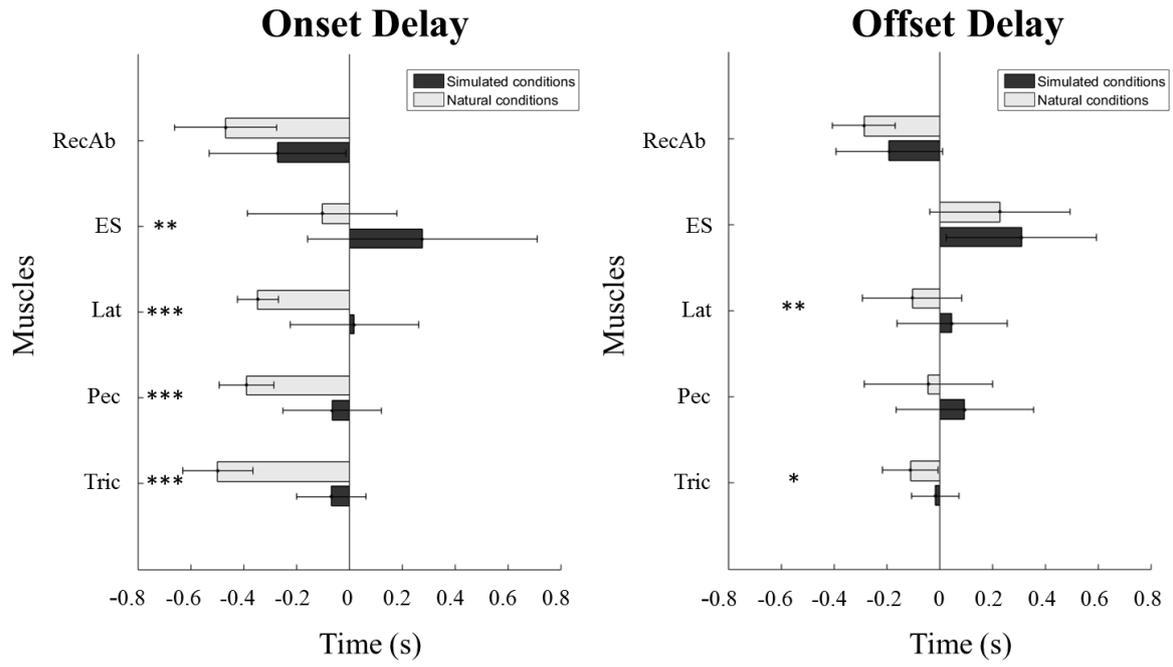
RecAb = Rectus Abdominis muscle

VO₂ = oxygen consumption

XC = cross-country







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Variable	simulated conditions	natural conditions	simulated conditions	natural conditions
	mean \pm SD	mean \pm SD	median \pm IQR	median \pm IQR
speed _{max} (m/s)	4.28 \pm 0.63*	4.61 \pm 0.67*	4.42 \pm 0.94*	4.68 \pm 1.16*
force _{impact} (N)	254.73 \pm 87.65	257.95 \pm 94.02	225.89 \pm 125.33	256.23 \pm 86.28
force _{peak} (N)	208.37 \pm 75.33	188.55 \pm 54.58	166.85 \pm 104.05	169.18 \pm 62.53
force _{avg} (N)	122.17 \pm 33.48	114.28 \pm 28.36	116.98 \pm 53.90	123.68 \pm 33.89
force _{int} (Ns)	59.91 \pm 16.60***	34.61 \pm 9.12***	54.74 \pm 17.25***	33.14 \pm 15.05***
CT (s)	0.89 \pm 0.15***	0.66 \pm 0.11***	0.93 \pm 0.20***	0.62 \pm 0.19***
PT (s)	0.47 \pm 0.08***	0.30 \pm 0.04***	0.46 \pm 0.14***	0.30 \pm 0.07***
RT (s)	0.42 \pm 0.08	0.36 \pm 0.08	0.43 \pm 0.12	0.32 \pm 0.15
TtP (s)	0.11 \pm 0.02	0.10 \pm 0.03	0.10 \pm 0.03	0.09 \pm 0.05
TtI (s)	0.04 \pm 0.01**	0.03 \pm 0.01**	0.04 \pm 0.01**	0.03 \pm 0.03**

Table 1. Maximal speed, force, and cycle characteristic values in the two conditions (simulated and natural) were reported as a mean \pm SD and median \pm IQR. These values were obtained averaging five cycles per each subject. The statistical differences between the two conditions were reported, * = $p < 0.05$, ** = $p < 0.01$, * = $p < 0.001$.**

Speed_{max} (m/s), maximal speed; force_{impact} (N), force at the impact; force_{peak} (N), peak force in the poling phase; force_{avg} (N), average force during poling phase; force_{int} (N), integral force during poling phase; CT (s), cycle time; PT (s), poling time; RT (s), recovery time; TtP (s), time to peak; TtI (s), time to impact.

Variable	Muscle	natural/simulated conditions	natural/simulated conditions
		mean \pm SD	median \pm IQR
EMG _{peak} (ratio)	Tric	1.07 \pm 0.48	0.95 \pm 0.38
	Pec	1.11 \pm 0.50	0.97 \pm 0.50
	Lat	0.85 \pm 0.19*	0.88 \pm 0.33*
	ES	1.12 \pm 0.26	1.11 \pm 0.25
	RecAb	0.95 \pm 0.34	0.93 \pm 0.44
aEMG (ratio)	Tric	0.94 \pm 0.39	0.92 \pm 0.39
	Pec	0.96 \pm 0.46	0.86 \pm 0.60
	Lat	0.80 \pm 0.22*	0.81 \pm 0.44*
	ES	1.40 \pm 0.53	1.27 \pm 0.99
	RecAb	0.73 \pm 0.35*	0.73 \pm 0.39*

Table 2. Muscular activation values in the two conditions (simulated and natural) were reported as a mean \pm SD and median \pm IQR. These values were obtained averaging the same five cycles per each subject used for the force and cycle characteristics estimation. The statistical differences between the two conditions were reported, * = $p < 0.05$.

EMG_{peak} (ratio), ratio between natural and simulated values of the muscle activity peak; aEMG (ratio), ratio between natural and simulated values of the average muscle activity; Tric, Triceps Brachii muscle; Pec, Pectoralis Major muscle; Lat, Latissimus Dorsi muscle; ES, Erector Spinae muscle; RecAb, Rectus Abdominis muscle.

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Valeria Rosso:



Laura Gastaldi:



Walter Rapp:



Stefan J. Lindinger:



Yves C. Vanlandewijck:



Vesa Linnamo:

