Muscle use during double poling evaluated by positron emission tomography

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Bojsen-Møller J, Losnegard T, Kemppainen J, Viljanen T, Kalliokoski KK, Hallén J. Muscle use during double poling evaluated by positron emission tomography. J Appl Physiol 109: 1895–1903, 2010. First published October 14, 2010; doi:10.1152/japplphysiol.00671.2010.—Due to the complexity of movement in cross-country skiing (XCS), the muscle activation patterns are not well elucidated. Previous studies have applied surface electromyography (SEMG); however, recent gains in three-dimensional (3D) imaging techniques such as positron emission tomography (PET) have rendered an alternative approach to investigate muscle activation. The purpose of the present study was to examine muscle use during double poling (DP) at two work intensities by use of PET. Eight male subjects performed two 20-min DP bouts on separate days. Work intensity was ~53 and 74% of peak oxygen uptake ($V_{O2peak}$), respectively. During exercise 188 ± 8 MBq of $[18F]fluorodeoxyglucose ([18F]FDG) was injected, and subsequent to exercise a full-body PET scan was conducted. Regions of interest (ROI) were defined within 15 relevant muscles, and a glucose uptake index (GUI) was determined for all ROIs. The muscles that span the shoulder and elbow joints, the abdominal muscles, and hip flexors displayed the greatest GUI during DP. Glucose uptake did not increase significantly from low to high intensity in most upper body muscles; however, an increased GUI ($P < 0.05$) was seen for the knee flexor (27%) and extensor muscles (16%), and for abdominal muscles (21%). The present data confirm previous findings that muscles of the upper limb are the primary working muscles in DP. The present data further suggest that when exercise intensity increases, the muscles that span the lumbar spine, hip, and knee joints contribute increasingly. Finally, PET provides a promising alternative or supplement to existing methods to assess muscle activation in complex human movements. $[18F]fluorodeoxyglucose; glucose uptake; Nordic skiing; cross-country skiing

THE NATURE OF CROSS-COUNTRY SKIING (XCS) has evolved over the last decades, and due to, e.g., the introduction of sprint skiing and mass starts, greater emphasis has been put on the high-speed propulsion techniques such as double poling (DP) (18, 32, 33). Therefore the ability to exert upper-body muscle power has become increasingly important (11, 19, 29, 31), but performance also relies on activation of muscles of the lower body (hip flexors, extensors, and hamstring muscles) (10, 39). The complex patterns of muscle activation during XCS in general, and more specifically the distribution of upper vs. lower body muscle exertion within all the different ski propulsion techniques, are not well examined. Further, limited information exists as to how muscle activation changes with increasing work intensity. Such information would increase the understanding of how the different techniques are optimally executed and would be beneficial for optimization and evaluation of training preparation and competition strategies.

Recent studies have assessed neuromuscular activation of both upper and lower body musculature during DP (11, 17) or other XCS techniques (20, 26, 34, 38, 41) by applying surface electromyography (SEMG). SEMG displays certain methodological limitations in general (5, 15), and specifically when applied during dynamic contractions (4). Moreover, by the nature of the method SEMG only enables assessment of superficial muscles. Therefore, when investigating complex whole body movements such as DP, supplemental and/or alternative methodologies are warranted. Recent gains in three-dimensional (3D) imaging techniques such as positron emission tomography (PET) and magnetic resonance imaging (MRI) have enabled acquisition of more detailed information with respect to muscle activation (6–8, 12, 14, 16, 22, 24, 35). Despite the high spatial resolution, PET has only been applied to a limited extent in complex sports movements such as cycling or running (8, 16, 23, 36), and not previously in movement tasks where both muscles of the upper and lower limbs contribute to propulsion such as in XCS.

The purpose of the present study was therefore to investigate muscle activity patterns and the relative contribution of single muscles or muscle groups during double poling at two different work intensities (distance training and high-intensity training) by using PET/MRI imaging.

MATERIALS AND METHODS

Ethical approval. All subjects were informed about the study procedures and potential risks and provided written informed consent befor participation. The participants were subjected to a an effective radiation dose of 7.1 ± 0.2 mSv. The study was conducted according to Good Clinical Practice and conformed to the Declaration of Helsinki and was approved by the Ethics Committee of the Intermunicipal Hospital District of Southwest Finland (34/180/2009).

Subjects. Eight healthy males (23 ± 2 yr of age, 182 ± 5 cm, 78 ± 4 kg), all highly skilled cross country skiers, volunteered for the study. All subjects had 10–15 yr of XCS training background; five subjects could be considered present or previous national elite-level skiers. Inclusion criteria were a maximal oxygen uptake > 60 ml·kg$^{-1}$·min$^{-1}$ (running test), high technical skiing abilities as evaluated by expert skiing coaches, and age between 20–30 yr. Exclusion criteria were any musculoskeletal injury that would interfere with DP, any metallic component operated into the body, and any regularly/periodically used medication.

Experimental overview. The subjects participated on seven separate experimental days. Days 1–4 included ergometer familiarization and assessment of $O_2$ uptake at different exercise intensities. On days 5 and 6 the subjects performed one 20-min bout of ergometer double poling at low and high intensities, respectively (see below) with the tracer $[18F]fluorodeoxyglucose ([18F]FDG) infused, and subsequently the subjects underwent a full-body PET scan. On day 7 a full-body
MRI scan was performed to serve as anatomic reference to the PET images.

**Study protocol.** On days 1 and 2, the subjects performed two 40-min familiarization training sessions in a commercially available DP ergometer (Thoraxtrainer, Holbæk, Denmark) fitted with customized snow ski poles (Swix CT1, Lillehammer, Norway) (Fig. 1). The resistance setting on the ergometer was set to “4” during all experiments. Individual pole lengths were used in all ergometer exercise bouts based on self-selected pole length during snow skiing (153 ± 4 cm or 84% of body height). Based on the power reading (W) on the ergometer display the subjects were asked to identify two individual target work loads, one that would correspond to the intensity of a 2–3 h of low-intensity training bout (distance training), and one corresponding to that of a hard 30-min constant-pace training session (high-intensity training). The defined target work loads were on average 70 ± 13 and 105 ± 20 W, and the subjects were required to exercise at their individual target intensities in the remaining part of the study (hereafter termed “low intensity” and “high intensity”).

It was not feasible to measure O$_2$ uptake (V$_{O2}$) on the days of PET scanning, so V$_{O2}$ during low and high intensities was therefore assessed in a separate session on day 3: the subjects did a brief warm-up and thereafter two 6-min bouts of DP on low and high intensity, respectively, was performed. Oxygen uptake was measured continuously, and V$_{O2}$ values were noted after 4–5.5 min of exercise (averaged over 90 s). Subsequent (5 min) to the high intensity bout the subjects underwent a DP peak V$_{O2}$ (V$_{O2peak}$) test: work load was set to high intensity for 1 min and hereafter increased by 15 W. After 2 min the subject was asked to increase the intensity with the goal of complete exhaustion between 4 and 6 min. V$_{O2}$ was measured continuously, and the highest value averaged over 1 min was taken to represent V$_{O2peak(DP)}$ in this session.

On day 4 a maximal running test was conducted on a treadmill (Woodway, Weil am Rein, Germany) to assess V$_{O2peak}$ during running [V$_{O2peak(R)}$]. Details regarding the equipment, protocol, and measurement of V$_{O2peak(R)}$ have been described recently in a paper from the present lab (19), but in brief, the subjects ran on a 10.5% incline with increasing speeds each minute until exhaustion. Days 1–4 were conducted for each subject within a 2-wk period, and each session was separated by at least 48 h.

The experimental protocol was similar on days 5 and 6: the subjects reported fasting (6 h) to the laboratory, and no strenuous exercise was allowed in the 24 h preceding the experiment. An electrical goniometer (GI80, Penny and Giles, Biometrics, Gwent, UK) was firmly secured on the lateral aspects of the upper arm and forearm to enable assessment of the elbow joint angle during DP. A biphasic contact switch (Noraxon, Inline Footswitch, Scottsdale, AZ) was positioned on the hypothenar at the point of contact between the pole rim and the hand to register the time-wise onset of load in the poling phase. The goniometer and the contact-switch were connected to a wireless transmitter (Noraxon Telemyo 2400T G2) from which signals were relayed to a personal computer (TM2400 wireless receiver PC card), enabling 500-Hz sampling of the goniometer and contact switch signals. The system allowed for real-time signal visualization during experiments. The wireless transmitter was secured to the lumbar-pelvic region with a waist belt, and a heart rate (HR) transmitter was positioned around the thorax to enable HR sampling using a Polar S610i (Polar Electro, Kempele, Finland).

The subjects rested in a supine position for ∼20 min during which an intravenous catheter was inserted into the antecubital vein. A small amount of saline was continuously administered to keep the catheter clear. The total amount of saline infused during the experiment was <100 ml. After an initial blood sampling via the catheter, the subjects were positioned in the ergometer and commenced exercise at the prescribed target intensity. The order of exercise intensity on days 5 and 6 was randomly chosen such that four subjects performed low intensity on day 5 and high intensity on day 6, and vice versa for the remaining subjects. During exercise, the subjects chose their DP technique freely with respect to poling frequency and joint range of motion, and a real-time power display (W) enabled subjects to keep the required target intensity throughout the task (monitored also by the experimental leader). After 5 min of exercise 188 ± 8 MBq of $[^{18}F]$FDG in 2 ml of saline was infused during a brief exercise recess (<1 min), and hereafter exercise was continued for an additional 15 min. During exercise the goniometer and contact switch signals were sampled in six 1-min periods spread evenly across the 20-min work period. HR and poling frequency (read from the ergometer display) were registered in the same time periods. Immediately after exercise cessation a blood sample was drawn to determine lactate concentration. Blood lactate concentration was measured in plasma (YSI 1500 Sport, Yellow Springs Instruments). For technical reasons the lactate (La–) data were based on six subjects only. Immediately after exercise the subject was placed supine in anatomic position on a scanner bed that facilitated longitudinal displacement into the gantry of the PET scanner (Siemens ECAT HR+, Knoxville, TN). Caution was taken to minimize any muscle activation after termination of exercise.

$[^{18}F]$FDG was produced as previously described (9). The PET imaging was performed either using GE Advance (General Electric Medical Systems, Milwaukee, WI) or CTI ECAT HR+ (Siemens Medical Systems, Knoxville, TN) PET scanner, which both operated in two-dimensional (2D) mode. The same scanner was used on both days for each individual. The GE Advance and HR+ scanners consist of 18 and 32 rings of bismuth germanate detectors (BGO) yielding 35 and 63 transverse slices spaced by 4.25 and 2.46 mm, respectively. The imaging field of view is 55 cm in diameter in both scanners and 15.2 cm (GE Advance) and 15.5 cm (HR+) in axial length. The whole body, starting from the head, was scanned in the alternating phases of a 5-min emission scan/position and a 2-min post-emission transmis-
tion scan/position. Altogether, scanning of the whole body took \( \sim 110 \) min.

In a separate session (day 7) a full-body MRI scanning (Philips Intera 1.5 T scanner, Philips Medical Systems, Best, The Netherlands) was performed to enable anatomic reference for the regions of interest (ROIs) within the PET images. During PET scanning radioactive markers were positioned at anatomic landmarks (acromion, chista iliaca, and caput fibula), and lipid pills were similarly positioned during MRI scanning to enable reference between MR and PET images.

**Biomechanical analysis.** During subsequent offline analysis the goniometer and contact switch data were evaluated by use of the Noraxon MyoResearch XP1.04 signal analysis software package (Noraxon). The elbow joint angle amplitude (ROM) (\(^\circ\)), poling frequency (Hz), duration of the total poling cycle (s), and the poling phase (s) and recovery phase (s) as defined by Holmberg et al. (11) were determined based on the goniometer and contact-switch signals. Approximately 100 poling cycles/subject were averaged.

**PET image processing.** All datasets were corrected for dead time decay and measured photon attenuation, and the images were reconstructed using iterative reconstruction. The axial and in-plane resolution of the reconstructed images was \( \sim 5 \) mm full-width at half-maximum.

**PET analysis.** To enable an overview, 3D volume-rendered images of the whole body were constructed by use of MRIcro 1.4 software (Chris Rorden, Georgia Institute of Technology, Atlanta, GA) (Fig. 2). Cross-sectional (transversal plane) ROIs were determined bilaterally for the following muscles/muscle groups on both the high-intensity and the low-intensity day: knee joint extensors, knee joint flexors (that also exerts a hip extension moment), hip extensors (gluteus maximus), hip flexors (psosas major), lumbar erector spinae, rectus abdominis, latissimus dorsi, teres major, pectoralis major, anterior and posterior deltoideus, upper trapezius, cervical erector spinae, triceps brachii, and biceps brachii. ROIs were also attained in the myocardium at the widest circumference of the heart. During analysis PET and MR images were placed in isometry on the same computer screen by use of the Vinci v.3. software (Max-Planck-Institute for Neurological Research, Köln, Germany), and PET ROI cross-sectional profiles were drawn based on MR images from the relevant anatomic site (Fig. 3). Depending on the anatomic configuration of muscles (length), the ROIs were constructed by combining three to eight adjacent scanning planes (each \( \sim 5 \) mm thick), from approximately the middle portion (longitudinally) of the relevant muscles. ROI volume and size were similar in the images obtained on the 2 days (Table 1) (the computer software enables ROIs to be copy-pasted between PET images). Standardized uptake value (SUV) of each muscle was calculated as SUV = tissue radioactivity concentration/(injected dose/subject body wt).

To serve as baseline reference for each day, additional PET ROIs were drawn within large bones: the femur condyles, the proximal tibia, and the calcaneus. A total of 12 bone ROIs was defined for each subject on each day. The passive tissue ROI volume was 18,270 ± 5,636 mm\(^3\) on the low-intensity day and 17,126 ± 3,808 mm\(^3\) on the high-intensity day, with mean SUV of 186 ± 40 and 190 ± 50, respectively. No significant difference was observed between days in either volume or mean reference tissue SUV, and a highly significant correlation \((R^2 = 0.80, P < 0.05)\) was observed in bone tissue SUV between days (Fig. 4). During subsequent analysis the GUI in the respective ROIs was calculated by dividing the tissue radioactivity (SUV) with bone radioactivity (SUV) × 100%, and GUI values below are given as SUV% of baseline (bone) values.

**Statistics.** Student’s two-tailed paired t-tests were used to evaluate differences in biomechanical parameters and GUI for all ROIs between low- and high-intensity days. Interday reproducibility for bone tissue SUV was assessed with linear regression analysis, and systematic bias was tested by use of a paired t-test. An alpha level of \( P < 0.05 \) was considered significant. Results are reported as group means (±SD).

**RESULTS**

**Work intensity and physiological response.** The \( \overline{V}O_2 \) during low- and high-intensity exercise was \( \sim 53 \) and 74% of \( \overline{V}O_2\text{peak}(DP) \) as measured during preexperimental days. The actual work intensities (W) and HR were comparable at the
low- and high-intensity exercise bouts on day 3 vs. those on the experimental days (days 5 and 6; Tables 2 and 3).

On days 5 and 6 (PET scanning days), the average work intensity (W) was 55% greater on the high-intensity day compared with that of the low-intensity day (Table 3). The corresponding HR was 29% greater on the high-intensity day relative to that of the low-intensity day, and blood lactate increased significantly (pre-post exercise) and sevenfold more during the high-intensity exercise compared with the low-intensity exercise bout (Table 3).

**Biomechanical analysis.** The elbow ROM during DP increased 8% from the low- to the high-intensity exercise. Poling frequency increased 14%, while the poling cycle time, the duration of the poling phase and the recovery phase decreased by 12% between intensities (all changes, \( P < 0.05 \)) (Table 3).

**PET analysis.** For the upper extremity muscles, the triceps brachii displayed by far the greatest GUI in general (≈4,400%; data averaged between low-intensity day and high-intensity day), followed by the latissimus dorsi (≈2,800%), the teres major (≈2,300%), the pectoralis (≈1,700%) and the posterior deltoid muscles (≈1,500%). The biceps brachii and the anterior deltoid muscles exhibited less GUI in comparison (≈800% and 400%, respectively) (Fig. 5).

Most upper extremity muscles exhibited higher numerical GUI values on the high-intensity day compared with that of the low-intensity day, but no significant differences were observed for this group of muscles between days. A tendency to a decrease in GUI was seen from low to high intensity for the triceps brachii (22%, \( P < 0.1 \)), and oppositely, a tendency to an increase (7%, \( P < 0.1 \)) was seen for the biceps brachii (Fig. 5).

For the central muscles of the body that span the lower spine a considerable GUI was observed (≈1,600%), and a significant increase of 21% (\( P < 0.05 \)) from the low- to the high-intensity day was seen for the rectus abdominis.

For the muscles that span the hip and knee joint the general GUI was lower compared with the muscles of the upper extremity (knee extensors: ≈500%; knee flexors: ≈800%; hip flexors: ≈1,100%; and hip extensors: ≈600%), but a significant increase (\( P < 0.05 \)) was observed from low to high intensity for the knee extensors (16%) and for the knee flexors (27%), while a tendency to increase (\( P < 0.1 \)) was seen for the hip flexors (82%).
Table 1. ROI volumes

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Low Intensity</th>
<th>High Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee flexors</td>
<td>449,413 ± 41,271</td>
<td>427,370 ± 44,311</td>
</tr>
<tr>
<td>Knee extensors</td>
<td>418,294 ± 59,785</td>
<td>398,654 ± 75,922</td>
</tr>
<tr>
<td>Hip flexors</td>
<td>48,911 ± 9,333</td>
<td>47,320 ± 6,657</td>
</tr>
<tr>
<td>Gluteus maximus</td>
<td>217,941 ± 43,191</td>
<td>212,598 ± 40,655</td>
</tr>
<tr>
<td>Rectus abdominis</td>
<td>54,976 ± 12,329</td>
<td>52,982 ± 9,774</td>
</tr>
<tr>
<td>Erector spinae (lumbar region)</td>
<td>123,522 ± 25,149</td>
<td>118,772 ± 22,777</td>
</tr>
<tr>
<td>Pectoralis major</td>
<td>114,589 ± 6,304</td>
<td>111,875 ± 8,045</td>
</tr>
<tr>
<td>Latissimus dorsi</td>
<td>195,973 ± 25,350</td>
<td>189,822 ± 24,681</td>
</tr>
<tr>
<td>Teres major</td>
<td>35,268 ± 4,999</td>
<td>36,064 ± 4,499</td>
</tr>
<tr>
<td>Anterior deltoid</td>
<td>35,192 ± 8,784</td>
<td>35,456 ± 9,218</td>
</tr>
<tr>
<td>Posterior deltoid</td>
<td>63,331 ± 9,186</td>
<td>63,363 ± 9,248</td>
</tr>
<tr>
<td>Triceps brachii</td>
<td>191,875 ± 27,353</td>
<td>193,499 ± 27,006</td>
</tr>
<tr>
<td>Biceps brachii</td>
<td>56,576 ± 4,460</td>
<td>60,017 ± 5,189</td>
</tr>
<tr>
<td>Cervical erector spinae</td>
<td>19,117 ± 4,403</td>
<td>19,208 ± 4,507</td>
</tr>
<tr>
<td>Trapezius</td>
<td>43,321 ± 15,903</td>
<td>43,235 ± 14,843</td>
</tr>
</tbody>
</table>

Values are means ± SD. Data are “total volumes” in mm³ such that regions of interest (ROIs) of contralateral muscles are added. No significant differences were observed between ROI volumes in any muscle or muscle group.

In the cervical region a high GUI was seen for the cervical part of the erector spinae (−2,400%), while the trapezius displayed a more moderate GUI (−800%).

The GUI in the myocardium was high (−3,000%) and decreased significantly (−39%, P < 0.05) from the low-intensity day to the high-intensity day (Fig. 5).

**DISCUSSION**

The present study adds to previous studies on muscle activation during double poling by providing a more detailed 3D picture of the involvement of different muscles. Novel findings are that the hip flexors seem to be highly involved especially at high intensity, but also that the posterior deltoid muscles and cervical spine extensors display high glucose uptake during DP. The data confirm previous studies in that the upper extremity muscles display markedly lower GUI; however, during simultaneous arm and leg exercise, glucose uptake can only to a limited extent be used to infer about the relative energy turnover of lower and upper limb muscles due to a high contribution from lactate oxidation to the energy turnover in the legs (39). In fact, the study of van Hall et al. (39) indicates an insignificant glucose uptake and a high lactate uptake and oxidation during double poling although it cannot be excluded that the preceding 40-min exercise in that experiment had an effect on the distribution between lactate and glucose utilization. The same experiment showed that oxygen uptake was similar in the lower and upper limbs during double poling at an intensity comparable to that of the high-intensity exercise in the present study (3). Hence, since the muscle mass is much greater in the legs, the activation relative to its maximum is likely much less. The relatively low leg muscle GUI in the present study is thus most likely a consequence of both a moderate activation and a high contribution from lactate oxidation, and the present data thus seem to fit well with previous work. Nonetheless, the present data add to previous studies by showing that muscle activation in the legs does not seem to be uniform, that the knee flexors are more activated than the extensors, and that muscles of the lower legs are only minutely activated.

Based on GUI, the central muscles of the body, i.e., the abdominal muscles that exert flexion in the lower spine and the hip flexors, seem to contribute significantly to DP. Moreover, taken together with findings in previous PET studies (REF) it seems plausible that an augmented GUI as seen between intensities in the present experimental setting is an indicator of increased muscle activation.

**Muscle use during DP**. Assuming that the GUI reflects muscle activation, the present data confirm that the main effector muscles in DP include the triceps brachii, latissimus dorsi, teres major, and the pectoralis muscles that all span the shoulder joint (11). The posterior deltoid muscles that belong to the same group but have not previously been assessed seem also to play an important role in DP.

Muscles of the lower extremity display markedly lower GUI; however, during simultaneous arm and leg exercise, glucose uptake can only to a limited extent be used to infer about the relative energy turnover of lower and upper limb muscles due to a high contribution from lactate oxidation to the energy turnover in the legs (39). In fact, the study of van Hall et al. (39) indicates an insignificant glucose uptake and a high lactate uptake and oxidation during double poling although it cannot be excluded that the preceding 40-min exercise in that experiment had an effect on the distribution between lactate and glucose utilization. The same experiment showed that oxygen uptake was similar in the lower and upper limbs during double poling at an intensity comparable to that of the high-intensity exercise in the present study (3). Hence, since the muscle mass is much greater in the legs, the activation relative to its maximum is likely much less. The relatively low leg muscle GUI in the present study is thus most likely a consequence of both a moderate activation and a high contribution from lactate oxidation, and the present data thus seem to fit well with previous work. Nonetheless, the present data add to previous studies by showing that muscle activation in the legs does not seem to be uniform, that the knee flexors are more activated than the extensors, and that muscles of the lower legs are only minutely activated.

Based on GUI, the central muscles of the body, i.e., the abdominal muscles that exert flexion in the lower spine and the hip flexors, seem to contribute significantly to DP. Moreover,
Table 2. Work load and physiological response at low, high, and maximal intensity in double poling and maximal intensity during treadmill running

<table>
<thead>
<tr>
<th>Days 3 and 4</th>
<th>Double Poling</th>
<th>Running V(\dot{V}O_2)max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Intensity</td>
<td>High Intensity</td>
<td>V(\dot{V}O_2)peak(DP)</td>
</tr>
<tr>
<td>Work load, W</td>
<td>69 ± 13</td>
<td>106 ± 20</td>
</tr>
<tr>
<td>(\dot{V}O_2), l/min</td>
<td>2.5 ± 0.2</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>139 ± 7</td>
<td>44.1 ± 5.0</td>
</tr>
<tr>
<td>VE, l/min</td>
<td>63.9 ± 7.0</td>
<td>105.4 ± 17.0</td>
</tr>
<tr>
<td>RER</td>
<td>0.88 ± 0.02</td>
<td>0.95 ± 0.02</td>
</tr>
</tbody>
</table>

Values are means ± SD. All data were acquired on days 3 and 4. "% of Max" denotes the value relative to that of maximal intensity double poling (DP). V\(\dot{V}O_2\), oxygen uptake; HR, heart rate; VE, ventilation; RER, respiratory exchange ratio; V\(\dot{V}O_2\)peak(DP), peak V\(\dot{V}O_2\) during DP; V\(\dot{V}O_2\)peak(R), peak V\(\dot{V}O_2\) during running. *Significant difference (P < 0.05) between exercise type (DP or treadmill running) at maximal intensity.

Table 3. Work load, physiological response, and biomechanical data acquired during low- and high-intensity DP on experimental days 5 and 6

<table>
<thead>
<tr>
<th>Days 5 and 6</th>
<th>Low-Intensity Day</th>
<th>High-Intensity Day</th>
<th>Difference Between Intensities, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work load, W</td>
<td>68 ± 14</td>
<td>106 ± 18*</td>
<td>55</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>128 ± 9</td>
<td>165 ± 4*</td>
<td>29</td>
</tr>
<tr>
<td>La(^-) before exercise, mmol/l</td>
<td>1.0 ± 0.2</td>
<td>1.0 ± 0.4</td>
<td>0</td>
</tr>
<tr>
<td>La(^-) after exercise, mmol/l</td>
<td>2.3 ± 1.6</td>
<td>4.4 ± 2.7*</td>
<td>309</td>
</tr>
<tr>
<td>Elbow ROM, °</td>
<td>75 ± 17</td>
<td>80 ± 13*</td>
<td>8</td>
</tr>
<tr>
<td>Cadence, strokes/min</td>
<td>76 ± 6</td>
<td>50 ± 7*</td>
<td>14</td>
</tr>
<tr>
<td>Pacing frequency, Hz</td>
<td>0.74 ± 0.11</td>
<td>0.83 ± 0.11*</td>
<td>14</td>
</tr>
<tr>
<td>Pacing cycle, s</td>
<td>1.38 ± 0.25</td>
<td>1.23 ± 0.19*</td>
<td>14</td>
</tr>
<tr>
<td>Pacing phase, s</td>
<td>0.91 ± 0.22</td>
<td>0.80 ± 0.19*</td>
<td>14</td>
</tr>
<tr>
<td>Recovery phase, s</td>
<td>0.48 ± 0.11</td>
<td>0.42 ± 0.12*</td>
<td>14</td>
</tr>
</tbody>
</table>

Values are means ± SD. Work load, HR, and poling data are averaged over the exercise bout. Blood samples for lactate (La\(^-\)) were drawn before and after exercise. ROM, range of motion. *Significant difference (P < 0.05) between low- and high-intensity exercise.

One previous study has performed detailed SEMG measurements during DP at 85% of maximum DP velocity (11). In this investigation the teres major, rectus abdominis, latissimus dorsi, pectoralis major, triceps, and gluteus maximus displayed high EMG activity, while lower extremity muscles scored medium to low EMG activity. Other studies have indicated that the triceps brachii and muscles around the shoulder joint are the main propulsors during DP (11, 17, 37), and as such the present PET data are comparable to previous findings obtained with SEMG. Differences in work intensity between present and previous studies, and further the different experimental setting (treadmill DP on roller skis vs. DP ergometer in the present study), may account for dissimilarities between studies. The present biomechanical data are not quite identical to what has previously been reported in treadmill and snow skiing: while poling frequencies were similar, the current poling times were longer, leading to a different phase distribution within the entire cycle (11). These differences likely pertain to mechanical constraints introduced by the ergometer such as flywheel inertia and resistance.

Low to high intensity. As noted the PET method is better suited to infer about changes between intensities within the same muscle or muscle group. The present data revealed similar values or nonsignificant gains between days in GUI for most muscles that exert moments about the shoulder joint. Concurrently, muscles in the lower part of the body (hip, spine, and leg muscles) showed significant increases in GUI from low to high intensity, which suggests that the relative contribution from these muscles increases with increasing work intensity. A recent study that examined diagonal stride found that blood flow, regional O\(_2\) delivery, and V\(\dot{V}O_2\) increased to a greater extent in legs compared with that of arm muscles when work intensity increased from submaximal to maximal efforts (2, 3). Although different ski techniques and intensities were used, and although the present study applies a highly different methodology, the studies, taken together, may indicate that arm and shoulder muscles reach a plateau in energy output at submaximal levels, and that further increases in whole body exercise intensity during DP is covered by muscles in the lower part of the body. This mechanism may also be related to muscle size, such that the relatively small muscles that operate about the shoulder and elbow joints are perhaps sufficient to keep a certain work intensity; however,
when intensity increases above a certain level the greater muscle mass of the lower body is required to encounter the global energy demand. In the present study a tendency to a decrease in triceps brachii GUI was observed from low to high intensity, which underscores this notion; however, these findings should be seen in the light of the above discussion on the limitation of the PET method that only quantifies glucose uptake and does not account for metabolism of other substrates. Nonetheless, it seems plausible that an increase in intensity can only be accomplished by a change in the DP technique toward greater involvement of muscles in the central and lower body.

Fig. 5. Muscle glucose uptake index (GUI). GUI for relevant muscles and muscle groups. Open bars denote GUI on the low-intensity day, while filled bars represent uptake on the high-intensity day. *P < 0.05 from day to day. (**) P < 0.1. Note individual y-axis scaling for the elbow joint and myocardium plots. Teres M., teres major.

Fig. 6. Heterogeneous activation of the triceps brachii. PET enables assessment of uneven activation within single muscles or muscle groups. The present individual displayed an activation strategy in which mainly the medial head of the triceps was activated. This difference would not have been accounted for in a study using surface electromyography (SEMG) if electrodes were only placed on one portion of the muscle as has previously been done. Red color denotes greatest glucose uptake.
Although not strictly pertinent for the general aim of the study, also ROIs were drawn in the heart muscle. This was deemed applicable since only a few previous studies have examined subjects in full-body PET scanning subsequent to two work intensities. In line with previous work (12, 16), a significant reduction in myocardial GUI was observed from the low to high intensity, which is likely attributed to utilization of lactate as muscle fuel in the heart. In the present study the reduction was ~40%, and thus the present data confirm those of Kemppainen et al. (16), who found a reduction of ~27% when going from a work intensity of 55% \( \dot{V}O_{2\max} \) to 75%.

PET methodology. The following issues should be kept in mind when interpreting PET data. PET displays poor time resolution such that if subjects change technique during exercise this is not reflected in results. It should further be noted that some tracer may remain in the blood at the cessation of exercise and may thus be taken up during the scan. Based on blood radioactivity, previous studies have estimated the remaining amount of tracer to be small (16), and combined with the fact that in the present study the scans were performed identically between days, the influence on day-to-day results is likely nominal. Moreover, with PET it is necessary to normalize glucose uptake when comparing tasks performed on different days: When glucose uptake is measured at rest, arterial or arterialized venous blood samples are taken, and quantitative glucose uptake values are calculated using graphical analysis, as described by Patlak and Blasberg (25). Blood sampling during complex dynamic tasks is challenging and therefore other approaches have been used. In simple strength tasks, where only limited muscle mass is activated, normalization has been done relative to passive muscle that is not affected by contraction (13, 24). In more complex endurance type work tasks, the glucose uptake has been quantified, for example, relatively to resting control groups (35). Thus no "gold standard" exists for exercise studies, but in the present study, muscle glucose uptake was related to that of bone tissue, assuming that glucose uptake here is largely unaffected by exercise intensity. The SUV of the reference tissue was low and similar between days with a high interday correlation (Fig. 4), despite a marked difference in exercise intensity. Taken together, the selected approach seems a feasible alternative for whole body exercise studies with FDG-PET.

PET vs. EMG. When comparing the methods it becomes clear that SEMG is a more practical method and thus seems more feasible to apply when investigating muscle use. SEMG does, however, present issues with respect to signal cancellation and cross talk, and in complex movements during which body segments are moving at high frequencies, also issues with respect to displacement of the skin (and thus electrodes) relative to the underlying muscles are apparent (4). EMG has a high time resolution, but poor spatial resolution, and in fact only the portion of muscle below the electrodes can be inferred about. Moreover, EMG requires normalization to maximal or peak EMG, which especially during dynamic contractions where muscle lengths change during the executed joint range of motion presents a confounding factor. In comparison, PET is more costly, complex, and time consuming; however, PET presents excellent spatial resolution, which allows for investigation of deeper lying muscles and portions of muscle that are not accessible with SEMG. Also individual activation strategies can be accounted for with PET: for example, one subject of the present study only used the medial portion of the triceps brachii in DP, which would not have been observed if the present experiment was conducted with for example EMG electrodes positioned on only one of the triceps portions (Fig. 6).

In conclusion, PET imaging may be considered a promising supplement or alternative to more traditional methods for investigating muscle use during complex human movements. The present data further suggest that although double poling is an upper body effort, also muscles that exert moments about the lumbar spine, hip, and knee joint play an increasingly important role for propulsion when exercise intensity increases.

Perspectives

The PET data and biomechanical assessments seem largely comparable to previous investigations (11, 31). The currently used DP ergometer resembles thus to a reasonable extent the DP movement during at least treadmill skiing and may thus be considered a relevant instrument for training and further research. The present study further suggests that low-intensity training may not be sufficient to target all muscles that are involved in high-speed DP, and specifically training intensities must be high to impact on muscles of the lower body. Surprisingly, a high GUI was observed in posterior neck muscles that do not contribute to propulsion. Personal communications with top-level skiers have confirmed that tiredness or specific muscle pain can be experienced in this region after excessive DP bouts. Specific resistance training of neck flexor muscles and/or stretching/mobilization may be relevant for athletes that frequently are engaged in high-speed DP.

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