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The effectiveness of stretch–shortening cycling in upper-limb extensor muscles during elite cross-country skiing with the double-poling technique

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ABSTRACT

This investigation was designed to evaluate the effectiveness of stretch–shortening cycling (SSC_{EFF}) in upper-limb extensor muscles while cross-country skiing using the double-poling technique (DP). To this end, SSC_{EFF} was analyzed in relation to DP velocity and performance. Eleven elite cross-country skiers performed an incremental test to determine maximal DP velocity (V_{max}). Thereafter, cycle characteristics, elbow joint kinematics and poling forces were monitored on a treadmill while skiing at two sub-maximal and racing velocity (85% of V_{max}). The average EMG activities of the *triceps brachii* and *latissimus dorsi* muscles were determined during the flexion and extension sub-phases of the poling cycle (EMG_{FLEX}, EMG_{EXT}), as well as prior to pole plant (EMG_{PRE}). SSC_{EFF} was defined as the ratio of $aEMG_{FLEX}$ to $aEMG_{EXT}$. EMG_{PRE} and EMG_{FLEX} increased with velocity for both muscles ($P < 0.01$), as did SSC_{EFF} (from 0.9 ± 0.3 to 1.3 ± 0.5 for the *triceps brachii* and from 0.9 ± 0.4 to 1.5 ± 0.5 for the *latissimus dorsi*) and poling force (from 253 ± 33 to 290 ± 36 N; $P < 0.05$). Furthermore, SSC_{EFF} was positively correlated to V_{max}, to EMG_{PRE} and EMG_{FLEX} ($P < 0.05$). The neuromuscular adaptations made at higher velocities, when more poling force must be applied to the ground, exert a major influence on the DP performance of elite cross-country skiers.

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1. Introduction

Double poling (DP) is an important classical cross-country skiing technique (Fabre et al., 2010; Stöggl et al., 2006) used primarily on the flatter sections of a course, when the velocity is high. Although the contribution by the legs is not negligible (Holmberg et al., 2006), the upper body generates most of the forward propulsion. During the poling phase of a DP cycle, symmetrical and synchronous actions of the upper limbs are exerted powerfully on the ground through the poles (Stöggl and Müller, 2009).

As in other types of animal and human locomotion (Dawson and Taylor, 1973; Hof et al., 2002; Roberts et al., 1997), stretch–shortening cycling (SSC) in some muscles is involved in propulsion during classical cross-country skiing (Komi and Norman, 1987; Lindinger et al., 2009a). SSC is defined as being present when a concentric muscular action is preceded by a short and rapid eccentric phase, during which external forces lengthen the muscles, and when muscular pre-activation is clearly observed (Komi, 2003). The energy stored in the elastic elements of tendon-muscular structures during the stretching phase enhances mechanical output during the subsequent concentric phase (Cavagna et al., 1968; Herzog and Leonard, 2002), in addition to improving the economy of muscle performance (Anderson and Pandy, 1993). Recently, the term "concerted contractions" has also been applied to define certain types of SSC (Kurokawa et al., 2003).

Early studies (Aura and Komi, 1986; Cavagna and Kaneko, 1977) revealed a positive correlation between the intensity of muscular stretching and the effectiveness of positive work. Consequently, the ratio between the average electromyographic signals recorded during the eccentric and concentric phases was developed as an index of the effectiveness of SSC (SSC_{EFF}). This index is related to the efficiency of positive work during SSC (Aura and Komi, 1986; Bosco et al., 1982), to the energetic cost of running and to the effects of fatigue (Abe et al., 2007; Avela et al., 1996; Bourdin et al., 1995).

Although muscle length during double poling has not yet been measured directly, certain extensor muscles in the upper limbs appear to undergo SSC (Lindinger et al., 2009a). The rapid flexion–extension pattern in the elbow and shoulder joints during the pol-

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ing phase (Lindinger et al., 2009a; Nilsson et al., 2013) and the associated activation of some of these upper-limb extensor muscles (Lindinger et al., 2009a) are similar to other cyclic exercises typically considered to involve SSC, such as running (Komi, 2000).

To our knowledge, no information concerning SSC_{EFF} in the extensor muscles of the upper limbs of cross-country skiers during DP and its relationship to performance has yet been reported. Accordingly, the aims of the present investigation were (i) to examine SSC_{EFF} in relationship to speed in two important extensor muscles of the upper limb during DP and (ii) to determine whether the SSC_{EFF} of these muscles influences DP performance in elite cross-country skiers.

2. Methods

2.1. Subjects

Eleven elite male Italian cross-country skiers who have competed in national and European races volunteered to participate. Their background characteristics and levels of performance (as evaluated by the Italian Federation of Winter Sports) are presented in Table 1. This study was pre-approved by the Ethical Committee of Verona University and all subjects were fully informed of its nature prior to providing their written consent to participate.

2.2. Overall design

First, the maximal velocity while DP skiing was determined for each participant. Thereafter, on another day (at least 48 h later), the experimental protocol involving three 5-min sessions of exercise at 14 and 16 km h^{-1} and at 85% of this maximal speed was carried out, with synchronized biomechanical measurements.

2.3. Instrumentation

All tests were performed with the DP technique on a 2.5 × 3.5-m motor-driven treadmill (Rodby Innovation AB, Vänge, Sweden) at an incline of 2°. The length of the poles (ONE WAY Sport Oy, Helsinki, Finland), which were equipped with special carbide tips, was what the skiers normally use for classical skiing (86.2 ± 1.1% of body height). To minimize variations in rolling resistance, all subjects used the same pair of classic roller skis with standard wheels (Ski Skett Nord CL, Crestani Sport, Sandrigo, Italy), which were prewarmed prior to each test by 20 min of roller skiing on the treadmill. The friction coefficient ($\mu = 0.024$) was assessed before testing as described previously (Pellegrini et al., 2011). During tests the subjects were secured via a safety harness to an emergency device above the treadmill. All of the participants had performed roller skiing on this treadmill previously in our laboratory and were thus familiar with the procedure.

Table 1
Background characteristics and levels of performance of the 11 elite male cross-country skiers who participated.

Parameter	Mean ± SD (range)
Age (years)	22.5 ± 3.2 (19–27)
Body height (m)	1.79 ± 0.05 (1.70–1.87)
Body mass (kg)	74.2 ± 6.0 (65.7–84.0)
Body mass index (kg m^{-2})	23.1 ± 1.3 (21.5–25.8)
V_{max} (km h^{-1})[a]	22.8 ± 1.2 (21.0–24.5)
FISI points[b]	45.5 ± 26.3 (14.6–92.5)

[a] Maximal velocity during an incremental treadmill skiing test to exhaustion employing the double poling technique.

[b] Performance level according to the Italian Federation of Winter Sports (FISI).

2.3.1. Force measurements

Single-axial force transducers (weight 15 g and custom-built by Delta-tech, Sogliano al Rubicone, Italy) were inserted beneath the handgrip of the poles (Bortolan et al., 2009). According to the skiers, these transducers did not interfere with poling. Prior to each test, the single-axial load cells were calibrated dynamically against a reference cell (546 QD; DS Europe srl, Milano, Italy). During measurements, the force signal was sampled at 200 Hz with a data acquisition board (NI DAQ-Pad-6016, National Instruments, Austin, TX, USA).

2.3.2. Kinematic measurements

A three-dimensional six-camera system (Qualisys AB, Gothenburg, Sweden), positioned around the treadmill, was used to monitor the displacement of the segments of the upper limbs. Hemispheric passive reflective markers were placed on the acromion, on the lateral epicondyle of the humerus, and on the radial styloid process of both upper limbs and their positions monitored at 100 Hz. The three-dimensional flexion–extension angular motion of the elbow was computed with the Qualisys software (QTools).

2.3.3. EMG measurements

A portable electromyographic system (Myomonitor®, Delsys Inc., Boston, MA, USA) recorded the surface activity of the *triceps brachii* (*caput laterale*) and *latissimus dorsi* muscles (on the dominant side only, to avoid impairment of movement by additional wires), both during the MVC and during the DP experimental trials. Parallel-bar EMG electrodes (DE-2.3 Single Differential Surface EMG Sensor; dimensions 41 × 20 × 5 mm, with two 10 × 1-mm Ag contacts 10 mm apart) were positioned on the belly of each muscle, longitudinally with respect to the underlying muscle fibers, in accordance with standard recommendations (Hermens et al., 2000; Konrad, 2005), to minimize cross-talk and geometrical artefacts (Rainoldi et al., 2000). A reference electrode was placed on the posterior aspect of the proximal epiphysis of the right radius.

To minimize impedance, the skin was shaved, slightly abraded, degreased and disinfected with alcohol before attaching the electrodes. The wires of the electrodes were kept close to the skin with elastic nets to avoid artifacts due to movement. The EMG signals were sampled at a frequency of 1000 Hz, hardware amplified (gain 1000 V/V ± 1%), band-pass filtered (20–450 Hz; 20 dB/oct) to remove noise, converted A/D and transmitted wirelessly (D-link WUA-1340 Wireless G USB adapter) to a computer for real-time data display and storage (EMGworks Acquisition Software, Delsys Inc., Boston, MA, USA). Full-wave rectification of EMG signals was performed before any further processing.

2.3.4. Synchronization of the instruments

During data acquisition, the instruments were synchronized by a digital trigger signal, following which data were collected for 30 s. All data were processed and analyzed with MATLAB 7.0 (The MathWorks, Inc., Natick, MA, USA), using a customized code.

2.4. Test protocol

2.4.1. Maximum voluntary isometric contractions (MVC)

In order to normalize the EMG amplitudes recorded during the experiment, each participant performed three standardized MVC (Acierno et al., 1995) for each muscle examined. Each MVC lasted 2–3 s, with 2 min of rest between consecutive contractions, and was performed on the dominant side (identified by asking the subjects to lift a heavy object with one upper limb).

The MVC of the *triceps brachii* muscle was performed in a fixed seated position, with the elbow in front of the trunk. Starting with

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