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Mechanical energy patterns in nordic walking: comparisons with conventional walking

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ABSTRACT

The use of poles during Nordic Walking (NW) actively engages the upper body to propel the body forward during walking. Evidence suggests that NW leads to a longer stride and higher speed, and sometimes to increased ground reaction forces with respect to conventional walking (W). The aim of this study was to investigate if NW is associated with different changes in body centre of mass (COM) motion and limbs energy patterns, mechanical work and efficiency compared to W. Eight experienced Nordic Walkers performed 5-min W and NW trials on a treadmill at 4 km h^{-1}. Steady state oxygen consumption and movements of body segments and poles were measured during each trial. We found greater fluctuation of kinetic (KE) and potential (PE) energy associated with COM displacement for NW compared to W. An earlier increase of KE for NW than for W, probably due to the propulsive action of poles, modified the synchronization between PE and KE oscillations so that a 10.9% higher pendular recovery between these energies was found in NW. The 10.2% higher total mechanical work found for NW was mainly due to the greater work required to move upper limbs and poles. NW was 20% less efficient and was metabolically more demanding than W, this difference could be ascribed to isometric contraction and low efficiency of upper musculature. Concluding, NW can be considered a highly dynamic gait, with distinctive mechanical features compared to conventional gait, due to pole propulsion and arm/pole swing.

1. Introduction

Nordic Walking (NW) is a form of physical activity in which conventional walking is supported by the use of specially designed poles. According to the International Nordic Walking Federation (INWA), the correct technique involves an active and dynamic use of the poles, and an inclined pole position during the loading phase, This actively engages the upper body in propelling the body forward during walking and implies two additional propulsive actions in the gait cycle. The propulsion originated through the pole of one side is mainly effective at the beginning of the stance phase of the contralateral leg, it is therefore not synchronous with the propulsive action of the leg [1,2].

Comparative studies conducted to characterize the kinematic differences between the two forms of locomotion have reported greater cycle length for NW than for W at the same speed [3] [4]. When the speed was a dependent variable, higher self-selected speed has been reported for walking with poles [5,6].

No differences were found between W and NW in ground reaction forces loading rate [1,7], ground reaction peak forces [1,3], joint moments [8], vertical ground reaction force at landing and knee joint shear and compression forces [1,3], were found not different between W and NW. Some studies reported increased vertical and horizontal ground reaction forces in landing phase during NW [2,6] or pole walking [9] compared to W. Evidence suggests therefore that the propulsive action delivered through poles effectively changes some of the features of the gait, leading to longer stride and higher speed, and in some case to increased ground reaction forces.

To our knowledge, nobody has yet studied whether the use of the poles causes changes in the locomotion pattern affecting the movement of the body centre of mass (COM). These data can

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provide a comprehensive description of the gait pattern, and outline differences in mechanical energy needed to sustain these two forms of locomotion against the external environment [10–12].

The aim of the present study is to investigate the effect of NW on the COM body segments' movements, as well as on the associated mechanical work and efficiency. We hypothesize that the pattern of movement might change in NW, resulting in a modified pattern of energy fluctuations and a higher mechanical work compared to conventional walking.

2. Methods

2.1. Subjects

The study population was eight male NW instructors licensed by the ANWI (Associazione Nordic Walking Italia) mean age 39.6 ± 12.6 years, height 1.81 ± 0.08 m, body weight 79.1 ± 8.7 kg, and with at least two years of experience in NW. The study was approved by the Ethical Committee of Verona University. All participants were informed about the nature and procedures of the study before they gave their written consent to participate.

2.2. Experimental procedure and protocols

Tests were performed on a motorized treadmill with a belt surface 2.5 m wide and 3.5 m long (RL3500E, Rodby, Sweden). Subjects used NW poles (Excel, Nordic Walker) equipped with special carbide tips to ensure appropriate grip with the treadmill surface. As recommended by the INWA, pole length was determined by multiplying the subject's height in cm by 0.68, with a tolerance of 2.5 cm. The subjects performed 5-min tests on the treadmill as conventional walking and NW at a speed of 4 km h^{-1}. During NW all subjects adopted the diagonal technique, which is the most common NW technique and is characterized by contralateral leg and arm coordination. All conditions were randomised.

Body centre of mass (COM) was determined by the position and the mass of body segments plus poles. Kinematic data were obtained at 200 Hz using an optoelectronic motion capture system (6 cameras, MCU240, ProReflex; Qualisys, Gothenburg, Sweden). The body was considered as divided into 11 rigid segments: head plus trunk, upper arms, lower arms, thighs, calves and feet. Reflective hemispheric markers were positioned on both sides of the body on the gleno-humeral joint, the lateral condyle of the humerus, the dorsal wrist, the greater trochanter, the lateral condyle of the femur, the lateral malleolus and the fifth metatarsal phalangeal joint. Two reflective markers were positioned on each pole; one was placed 40 cm from the top of the pole, and the other was placed 40 cm above the tip of the pole. Data was filtered with a fourth-order low-pass Butterworth filter using a cut-off frequency based on residual analysis [13].

A circular pressure sensitive resistive membrane (DC-F01, Delsys Inc., Boston, MA, USA) was attached under the heel to detect contact of the foot with the ground.

Gas exchange and ventilatory parameters were collected breath-by-breath during the whole 5-min trial by means of a portable metabolic system (Cosmed K4b2, Rome, Italy). Before each test, the system was calibrated according to the manufacturer instruction.

2.3. Data processing

The gait stride was defined as beginning at the heel ground contact and ending at the subsequent ground contact of the same heel. Stride frequency (sf) and duty factor (df), defined as the relative duration of the stance phase over stride time, were then calculated. Ranges of inclination were determined for upper arm, lower arm and poles within each stride.

Body COM position was calculated from the position of centre of mass of each segment and from the mass of each segment, as obtained from the Dempster table [14]. The centre of mass of poles was determined as the position where a fulcrum maintained the objects in equilibrium.

The kinetic ($KE = 0.5Mv^2_{COM}$) and gravitational potential ($PE = Mgh_{COM}$) energy of COM were determined by calculating v_{COM}(the instantaneous velocity of COM in the sagittal plane with respect to a reference system moving at the treadmill belt speed), h_{COM} (the height of COM in the vertical direction with respect to the treadmill belt height) and by knowing M (the subject's body mass) and g (the gravitational acceleration).

The work necessary to sustain the KE changes (W_{KE}) and the PE changes (W_{PE}) was estimated by calculating respectively the sum of positive increments of KE and PE [15]. The total energy of COM due to its motion in the sagittal plane, TE, was calculated as the algebraic sum at each instant of PE and KE. The external mechanical work was determined W_{EXT} as the sum of positive increments of TE [10,12]. In accordance with other investigations, negative energy changes were not computed here, considering that the cost of negative work is about one fifth that of positive work [10,12]. The degree of the possible energy exchange between PE and KE was quantified by calculating the percentage recovery of mechanical energy, R%, which accounts for how much energy can be saved through a pendulum-like locomotion [10] as:

$$R\% = \frac{W_{PE} + W_{KE} - W_{EXT}}{W_{PE} + W_{KE}} x100 \tag{1}$$

We also calculated the percentage recovery at each instant of the cycle R(t) as proposed by Cavagna and colleagues [16]:

$$R(t) = \frac{|W_{PE}(t)| + |W_{KE}(t)| - |W_{EXT}(t)|}{|W_{PE}(t)| + |W_{KE}(t)|} x100 \tag{2}$$

The phase shift was defined as $\alpha = 360^{\circ}Dt.\tau^{-1}$, where Δt is the difference between the time at which KE is at a maximum and the time at which PE is at a minimum and τ is the step period [17].

The calculation of W_{int} was done from the kinetic energy of each segment due to their movements relative to the COM, KE_i, which is obtained from the sum of its translational and rotational energy, the first and the second term of Eq. (3) respectively.

$$KE_i = \frac{1}{2} m_i {v_{r,i}}^2 + \frac{1}{2} I_i {\omega_i}^2 \tag{3}$$

where m_i is the mass, $v_{r,i}$ is the speed relative to body COM, I_i the moment of inertia, ω_i the rotational velocity of the i-th segment.

For NW, the calculation of W_{int} the poles were considered as extra segments added to the arms (W_{int}^*). The moment of inertia of the poles about its mediolateral axis was calculated by modelling each pole as two shafts, divided by the COM poles, and two punctual masses, one corresponding to handgrip and one to the tip of the pole. The moment of inertia for a 1.20 m long pole was found to be 0.0266 kg*m^2.

For the calculation of W_{int}, we assumed that the energy can be transferred only among segments of the same limb [12]. In order to account separately for the contribution of trunk, upper and lower limbs, we calculated W_{int_trunk}, as the sum of increments of energy curves of the trunk, W_{int_arms}, as the sum of increment of energy curves after adding together the energies of upper arms, lower arms and poles. Then, W_{int_legs}, as the sum of increment of energy curves after adding together the energies of thighs, calves, and feet.

Furthermore, we calculated the work to move all the segments W_{int}, by adding up W_{int_arms}, W_{int_trunk} and W_{int_legs}. We also calculated the work needed to move segments and poles in NW, W_{int}^* by adding $W_{int\_arms}^*$, W_{int_trunk} and W_{int_legs}.