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Mechanical energy patterns in nordic walking: comparisons with conventional walking

Barbara Pellegrini[a,b,*], Leonardo Alexandre Peyré-Tartaruga[c], Chiara Zoppirolli[a,b], Lorenzo Bortolan[a,b], Aldo Savoldelli[a,b], Alberto Enrico Minetti[d], Federico Schena[a,b]

[a] CeRiSM (Research Centre in Mountain Sport and Health), University of Verona, Rovereto, Italy
[b] Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy
[c] Exercise Research Laboratory, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
[d] Laboratory of Physiomechanics of Locomotion, Department of Pathophysiology and Transplantation, University of Milan, Milan, Italy

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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

* Corresponding author at: CeRiSM, Research Centre in Mountain Sport and Health, University of Verona, Via Matteo del Ben 5/B 38068 Rovereto, (TN) Italy.
E-mail address: barbara.pellegrini@univr.it (B. Pellegrini).

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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:

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

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

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

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.

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

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}.

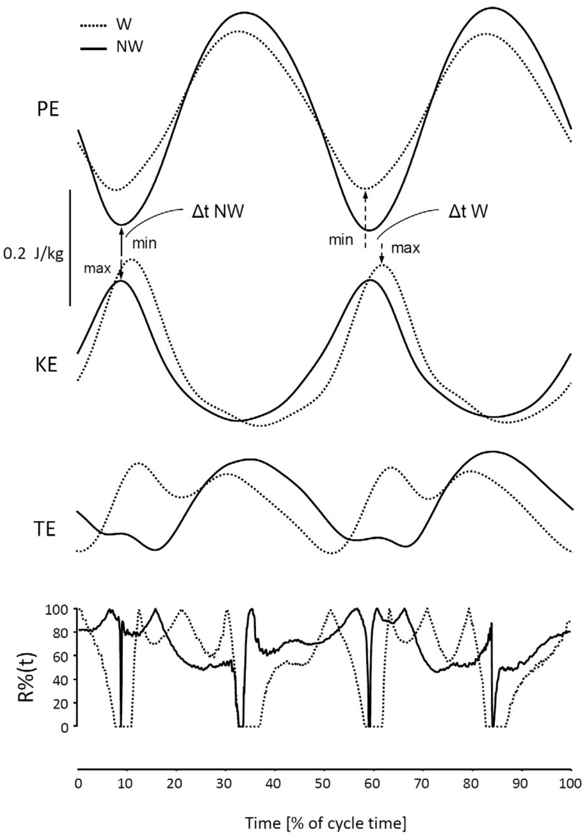

Fig. 1. From the upper to the lower part of the figure, PE, KE and TE = PE + KE energies and the curves R(t) indicating the time course of recovery are represented for a gait cycle for W and NW respectively with dotted and solid lines. The curves represented here are obtained by time normalizing and averaging data from 12 consecutives cycles for all subjects (Standard deviations curves were omitted to improve graph readability).

Total mechanical work to sustain the locomotion, W_{TOT} was calculated as the sum of W_{EXT} and W_{int}. Work was calculated over 12 complete cycles and was expressed per metre of distance travelled and unit of body mass. The average value of oxygen consumption ($\dot{V}O_2$), was calculated over the last 40 s of each condition. The net metabolic cost per unit of distance (C) was calculated from the ratio between the difference in $\dot{V}O_2$ at steady state minus $\dot{V}O_2$ at rest and the speed maintained on the treadmill. This value was expressed in $J \cdot kg^{-1} \cdot m^{-1}$ by converting the net $\dot{V}O_2$ to the corresponding metabolic energy output using an energy equivalent of O_2 depending on respiratory quotient[18]. Efficiency (Eff) was then computed as the ratio between C and W_{TOT} [10].

All data were processed using Matlab 7.0 (MathWorks Inc., Natick, MA, USA) and Excel 2003 (Microsoft Corporation, Redmond, Washington, USA).

2.4. Statistical analysis

The normality of the data was checked with the Shapiro-Wilk test. Paired samples *t*-tests were conducted to analyze the differences between gaits. Significance was set at $p \leq 0.05$. Where statistical differences were found, effect sizes (Cohen's d) were calculated [19]. SPSS 15.0 for Windows was used for all statistics.

3. Results

Lower sf and unchanged df were found for NW compared to conventional W. The oscillations of the PE and the KE for NW were significantly higher than for W (Fig. 1 and Table 1). The peak of the KE occured earlier than the valley of the PE in the gait cycle for NW, different from W where the peak and valley, respectively, were tuned (Fig. 1). A better synchronization of maximum of the PE with the minimum of the KE resulted in R(t) with a limited or even no time period where the pendulum recovery was zero for NW. On the contrary, regions with R(t) dropping to zero were found for W shortly after COM is at the highest point. This is due to a late increase of KE when PE is already dropping, thereby indicating that the pendulum mechanism is not working for those phases.

The plot of PE versus KE (Fig. 2) showed that during the time phase corresponding to the decrease of PE, the plot was much strighter for NW (panel B) than for W (panel A), showing a good coupling between the decrease of PE and increase of KE. The

Table 1
Values represent means ± s.d. for all participants. P values associated to the t student test for paired data are reported. The values marked with the asterisk represent parameters obtained by including in the calculation the mass of the poles.

	W		NW					
	Mean	±SD	Mean	±SD	P value	% diff	ES	
sf [Hz]	0.851	±0.059	0.758	±0.048	<**0.001**	−**10.93**	**2.5**	Large
df [%]	61	±3	60	±4	0.090	− 1.68		
W_{KE} [$J\,kg^{-1}\,m^{-1}$]	0.321	±0.058	0.378	±0.097	**0.035**	**16.9**	**0.665**	Large
W_{PE} [$J\,kg^{-1}\,m^{-1}$]	0.428	±0.082	0.521	±0.119	**0.034**	**20.3**	**0.967**	Large
W_{EXT} [$J\,kg^{-1}\,m^{-1}$]	0.316	±0.045	0.337	±0.104	0.680	3.9		
R%	57	±8	63	±8	**0.016**	**10.8**	**0.754**	Large
phase delay [°]	23.62	±4.53	−4.26	±2.45	**0.000**	**−91**	**6.47**	Large
W_{int_trunk} [$J\,kg^{-1}\,m^{-1}$]	0.006	±0.001	0.008	±0.005	0.323	30.53		
W_{int_arms}[$J\,kg^{-1}\,m^{-1}$]	0.029	±0.020	0.032	±0.012	0.47	13.0		
W_{int_legs} [$J\,kg^{-1}\,m^{-1}$]	0.182	±0.013	0.161	±0.016	<**0.001**	−**11.5**	**1.39**	Large
W_{int} [$J\,kg^{-1}\,m^{-1}$]	0.216	±0.026	0.202	±0.020	<**0.001**	−**6.4**	**0.595**	Large
W_{TOT} [$J\,kg^{-1}\,m^{-1}$]	0.532	±0.057	0.528	±0.097	0.057	−0.8		
W_{int_arms}*[$J\,kg^{-1}\,m^{-1}$]	0.029	±0.020	0.089	±0.024	<**0.001**	**212**	**2.76**	Large
W_{int}* [$J\,kg^{-1}\,m^{-1}$]	0.216	±0.026	0.263	±0.026	<**0.001**	**19.3**	**1.52**	Large
W_{TOT}* [$J\,kg^{-1}\,m^{-1}$]	0.532	±0.057	0.586	±0.096	**0.0046**	**10.2**	**0.68**	Large
ROM trunk [°]	5.9	±1.9	6.9	±1.7	0.348	16.2		
ROM upperarm [°]	27	±11	38	±12	**0.010**	**41.8**	**0.975**	Large
ROM forearm [°]	47	±16	79	±12	**0.004**	**65.2**	**2.151**	Large
ROM pole [°]			32	±6				
$\dot{V}O_2$ [$ml\,kg^{-1}\,min^{-1}$]	14.0	±1.9	17.3	±3.3	**0.001**	**23.6**	**1.725**	Large
$\dot{V}O_2$ [$ml\,kg^{-1}\,m^{-1}$]	0.0162	±0.0022	0.0200	±0.0038	**0.001**	**23.6**	**1.725**	Large
Eff	0.193	±0.042	0.154	±0.026	**0.014**	**20.2**	**1.537**	Large

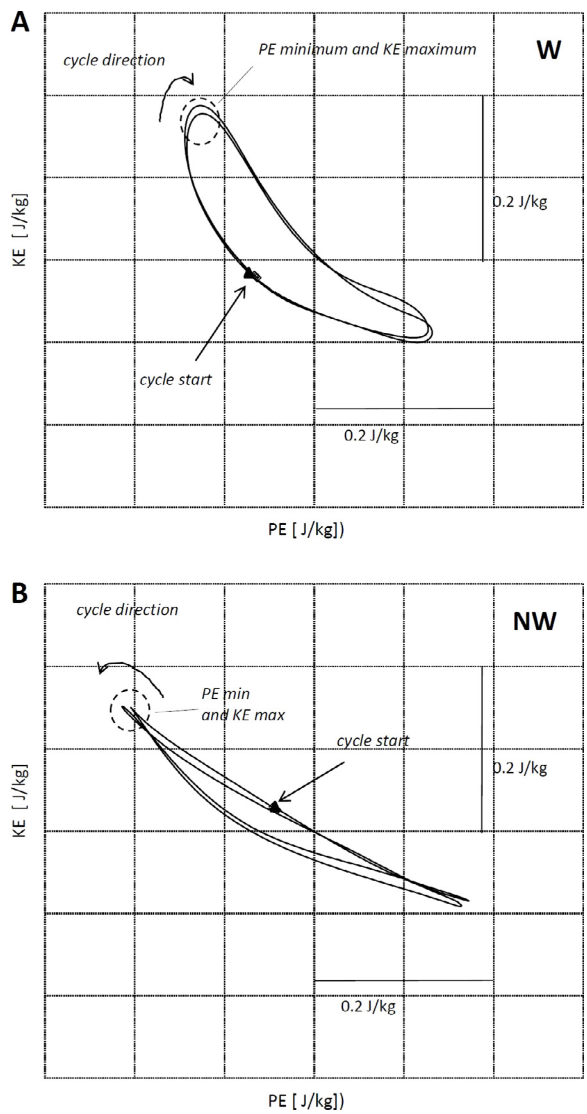

Fig. 2. PE vs KE plot for W (panel A) and NW, panel B. The curves are averaged data over all subjects. The beginning of the gait cycle is indicated with a filled triangle. The region where the PE and KE reach respectively their minimum and maximum is indicated with a dashed circle.

inclination of the Lissajous figures is around 45° for both gaits, although more inclined in NW, indicating an approximately out of phase coupling. According to Fig. 2, the reversal phases, where the energies change sense, in NW was abrupt as in a frictionless inverted-pendulum and, in W the reversions were smoother, less pendular. Also in Fig. 2, both in the up and down intermediary phases, when the COM went upwards and downwards, respectively, the pendulum-like recovery was more linear in NW.

The direction of rotation in the region in which KE reached its maximum and PE its minimum was clockwise for W and counter-clockwise for NW suggesting respectively a positive and negative delay of KE with respect to PE. Stride frequency was 11% lower for NW compared to W (Table 1). Higher R% and smaller phase delay between PE and KE were found for NW. Consequently, despite W_{PE} and W_{KE} were largely higher for NW than for W, W_{EXT} was not significantly different between gaits. No differences were found in W_{int_trunk} between gaits. Value for $Wint_{\_legs}$ was found to be lower for NW than for W. Conversely, W_{int_arms} was found to be not significantly different and when including the poles, $W_{int\_arms}{}^{*}$ was greater for NW than for W. Significantly greater ROM was found for upper- and forearm in NW condition. Total internal work was significantly lower for NW when excluding the poles and higher when including the poles, W_{TOT} was significantly higher for NW than for W only considering the contribution of the poles (Fig. 3).

Oxygen uptake ($\dot{V}O_2$) was found to be significantly increased by 23.6% in the NW condition compared to W and mechanical efficiency was lower for NW than for Walking (Table 1).

4. Discussion

To the best of our knowledge, this is the first study that has analyzed how the propulsive action of the upper body through the poles changes mechanical work of locomotion. The main new finding is that, although NW shows a major pendulum-like energy recovery compared to conventional walking, the greater dynamical motion of COM and the swing of arms and poles, results in a higher mechanical work and energy expenditure and lower metabolic efficiency.

The curves for potential and kinetic energy show greater oscillations for NW than for W, suggesting that walking with poles would lead to a more oscillating gait, as seen by different studies investigating ground reaction forces [2,6] and joint moments [3].

Nevertheless, the metabolic effect of the major vertical excursion is counterbalanced by a better pendular transduction in NW. Interestingly, Massaad and colleagues [20] reported similar findings comparing mechanical work and oxygen consumption in normal and bouncy walking, leading us to confirm the NW as a bouncy modality of walking. Changes in time of maximum KE cause a closer synchronization with the minimum PE, together with a more rapid rise of KE after the COM has reached his highest point, resulting in a greater recovery coefficient for NW compared to W. The action of the pole, therefore, leads to changes in the shape of energy-time curves enhancing the energy recovery by pendulum mechanism, that is already high in conventional walking. The main determinant of greater total mechanical work in NW than in W is the internal mechanical work. Although there is a higher internal mechanical work for NW compared to W, the work associated with the motion of the legs (W_{int_legs}) was lower. It is well known that the internal work is positively correlated with the stride frequency [11,21,22]. The lower work associated with the

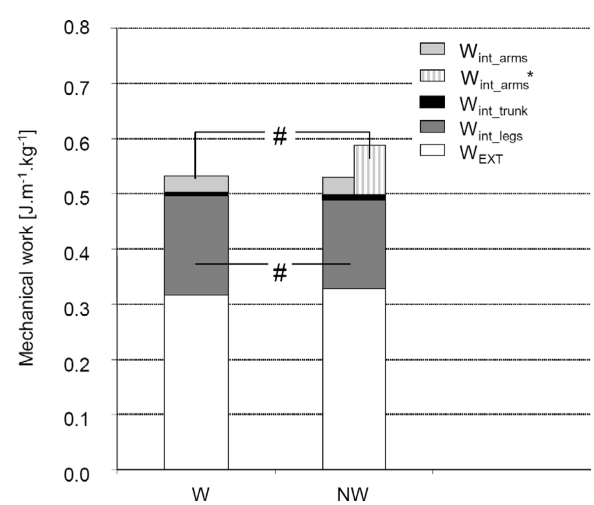

Fig. 3. Mean values of mechanical work for W and NW. W_{int} is represented in its component, W_{int_legs} $W_{int\_trunk,}$ W_{int_arms} (excluding poles mass), and $W_{int\_arms}{}^{*}$ (considering poles mass). Asterisk indicates statistical significant differences between W and NW, # = $p < 0.05$.

motion of the legs during NW with respect to W can be therefore ascribed to the lower stride frequency. The work to accelerate the upper limbs relative to COM (W_{int_arms}) appears to more than compensate the minor W_{int_legs}, even increasing the total mechanical work for NW. Conversely, the work needed to move the arms increased by about 30% when accounting for the pole masses. However, when neglecting the presence of the poles in the calculation of the internal work for NW, it was not significantly different from that found for walking. The increased range of motion of upper arm (+ 42%) and forearm (+65%) for NW in comparison to walking therefore do not result in a greater internal work for moving the limb, due to the decreased tempo.

Despite the low weight of poles, (0.235 kg in our investigation, about 1/7 of the forearm-hand segment weight), their contribution to mechanical work is not negligible. Due to their length, their moment of inertia indeed is one third of that of the forearm-hand segment. Moreover, being located distally from shoulder and joints, the poles underwent huge translation, greatly contributing to internal work. The internal work is determined by three variables: horizontal speed (v), stride frequency (sf) and duty factor (df) and one constant called q [21]. The latter reflects the inertial properties of limbs and is an invariant under different speeds and gradients [22,23], however, it is affected by the addition of poles. In fact, when we replace the variables that determine the internal mechanical work in the equation model [$W_{int} = v\ \mathrm{sf}\ (1 + (\mathrm{df}/(1 - \mathrm{df}))^2)\ q$] and we also include the proper W_{int} experimentally measured, the q calculated were as follows: 0.044 ± 0.018 *versus* 0.096 ± 0.033 for walking and NW respectively (ratio $q_W/q_{NW} = 0.455$). We found therefore that the changes of inertial properties of the limb is the main factor responsible for the greater mechanical work produced by upper limbs for NW in comparison to W. The work calculations presented here are based on the work-energy principle and follow a methodology commonly adopted for locomotion, when the direct knowledge of the forces acting on the body cannot be identified [15]. This methodology however, requires the making of many assumptions that might influence the results. In particular, having assumed the transfer between energies as possible, %R calculated here represents the upper limit of possible transfer between energies and W_{EXT} correspond to the low boundary. The effects of the different assumptions have been explored in detailed by Williams and Cavanagh [24]. We believe that, despite these limitations, the method is still valuable in comparing Nordic Walking with conventional walking.

The increase in energy expenditure, similarly to that found in previous studies [25–27], lead to a lower mechanical efficiency for NW compared to conventional walking. The reduction of efficiency may be explained by the relatively low efficiency of upper musculature and their contribution to work production for this form of locomotion [28,29]. Furthermore, walking with poles might require isometric and muscle coactivation in the upper body, not necessary in conventional walking[30–32]. These contractions will results in increased energy expenditure without any increase in mechanical work, which will lead to a reduction of the efficiency.

5. Conclusion

This investigation shows that the propulsion made through the pole in Nordic Walking greatly affects the mechanics of locomotion, resulting in greater energy fluctuations, higher mechanical work and energy expenditure, and a lower efficiency.

Conflict of interest statement

All authors disclose any financial and personal relationships with other people or organizations that could have inappropriately influenced the present work. All authors have no conflict of interest to disclose

References

[1] S.B. Jensen, M. Henriksen, J. Aaboe, L. Hansen, E.B. Simonsen, T. Alkjaer, Is it possible to reduce the knee joint compression force during level walking with hiking poles? Scand. J. Med. Sci. Sports 21 (2011) e195–e200.

[2] F.L. Kleindienst, K.J. Michel, J. Schwartz, B. Krabbe, Comparison of kinematic and kinetic parameters between the locomotion patterns in Nordic Walking, walking and running, Sportverletz Sportschaden 20 (2006) 25–30.

[3] L. Hansen, M. Henriksen, P. Larsen, T. Alkjaer, Nordic Walking does not reduce the loading of the knee joint, Scand. J. Med. Sci. Sports 18 (2008) 436–441.

[4] A.K. Dziuba, G. Zurek, I. Garrard, I. Wierzbicka-Damska, Biomechanical parameters in lower limbs during natural walking and Nordic walking at different speeds, Acta Bioeng. Biomech. 17 (2015) 95–101.

[5] J. Willson, M.R. Torry, M.J. Decker, T. Kernozek, J.R. Steadman, Effects of walking poles on lower extremity gait mechanics, Med. Sci. Sports Exerc. 33 (2001) 142–147.

[6] A. Encarnacion-Martinez, P. Perez-Soriano, S. Llana-Belloch, Differences in ground reaction forces and shock impacts between nordic walking and walking, Res. Q. Exerc. Sport 86 (2015) 94–99.

[7] M. Hagen, E.M. Hennig, P. Stieldorf, Lower and upper extremity loading in nordic walking in comparison with walking and running, J. Appl. Biomech. 27 (2011) 22–31.

[8] F. Stief, F.I. Kleindienst, J. Wiemeyer, F. Wedel, S. Campe, B. Krabbe, Inverse dynamic analysis of the lower extremities during nordic walking, walking, and running, J. Appl. Biomech. 24 (2008) 351–359.

[9] E.A. Brunelle, M.K. Miller, The effects of walking poles on ground reaction forces, Res. Q. Exerc. Sport 69 (1998) 30–31.

[10] G.A. Cavagna, M. Kaneko, Mechanical work and efficiency in level walking and running, J. Physiol. 268 (1977) 467–481.

[11] A.E. Minetti, F. Saibene, Mechanical work rate minimization and freely chosen stride frequency of human walking: a mathematical model, J. Exp. Biol. 170 (1992) 19–34.

[12] P.A. Willems, G.A. Cavagna, N.C. Heglund, External, internal and total work in human locomotion, J. Exp. Biol. 198 (1995) 379–393.

[13] D.A. Winter, Biomechanics and Motor Control of Human Movement, John Wiley & Sons Inc., 2009.

[14] W.T. Dempster, G.R.L. Gaughran, Properties of body segments based on size and weight, Am. J. Anat. 120 (1967) 33–54.

[15] V.M. Zatsiorsky, Kinetics of human motion – chapter 6, Mechanical Work and Energy in Human Movement, Leeds: Human Kinetics, Champaign, 2000 II.

[16] G.A. Cavagna, P.A. Willems, M.A. Legramandi, N.C. Heglund, Pendular energy transduction within the step in human walking, J. Exp. Biol. 205 (2002) 3413–3422.

[17] G.A. Cavagna, P. Franzetti, T. Fuchimoto, The mechanics of walking in children, J. Physiol. 343 (1983) 323–339.

[18] F. Peronnet, D. Massicotte, Table of nonprotein respiratory quotient: an update, Can. J. Sport Sci. 16 (1991) 23–29.

[19] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, 2nd edition, Lawrence Erlbaum, New Jersey, 1988.

[20] F. Massaad, T.M. Lejeune, C. Detrembleur, The up and down bobbing of human walking: a compromise between muscle work and efficiency, J. Physiol. 582 (2007) 789–799.

[21] G.A. Cavagna, P. Franzetti, The determinants of the step frequency in walking in humans, J. Physiol. 373 (1986) 235–242.

[22] A.E. Minetti, A model equation for the prediction of mechanical internal work of terrestrial locomotion, J. Biomech. 31 (1998) 463–468.

[23] F. Nardello, L.P. Ardigo, A.E. Minetti, Measured and predicted mechanical internal work in human locomotion, Hum. Mov. Sci. 30 (2010) 90–104.

[24] K.R. Williams, P.R. Cavanagh, A model for the calculation of mechanical power during distance running, J. Biomech. 16 (1983) 115–128.

[25] T. Schiffer, A. Knicker, U. Hoffman, B. Harwig, W. Hollmann, H.K. Struder, Physiological responses to nordic walking, walking and jogging, Eur. J. Appl. Physiol. 98 (2006) 56–61.

[26] T.S. Church, C.P. Earnest, G.M. Morss, Field testing of physiological responses associated with Nordic Walking, Res. Q. Exerc. Sport 73 (2002) 296–300.

[27] E.A. Hansen, G. Smith, Energy expenditure and comfort during Nordic walking with different pole lengths, J. Strength Cond. Res. 23 (2009) 1187–1194.

[28] R.G. Eston, D.A. Brodie, Responses to arm and leg ergometry, Br. J. Sports Med. 20 (1986) 4–6.

[29] J. Kang, E.C. Chaloupka, M.A. Mastrangelo, J. Angelucci, Physiological responses to upper body exercise on an arm and a modified leg ergometer, Med. Sci. Sports Exerc. 31 (1999) 1453–1459.

[30] P.O. Astrand, B. Ekblom, R. Messin, B. Saltin, J. Stemberg, Intra-arterial blood pressure during exercise with different muscle groups, J. Appl. Physiol. 20 (1965) 253–256.

[31] B. Pellegrini, L.A. Peyre-Tartaruga, C. Zoppirolli, L. Bortolan, E. Bacchi, H. Figard-Fabre, et al., Exploring muscle activation during nordic walking: a comparison between conventional and uphill walking, PLoS One 10 (2015) e0138906.

[32] H. Thys, P.A. Willems, P. Saels, Energy cost, mechanical work and muscular efficiency in swing-through gait with elbow crutches, J. Biomech. 29 (1996) 1473–1482.