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The evaluation of energy cost of effort and changes of centre of mass (COM) during race walking at starting speed after improving the length of lower extremities

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The purpose of the study was to evaluate the influence of extremities length improvement in the form of special shoe orthoses on the walking energy cost of the leading Polish representative in race walking.

Before a proper study, the aerobic capacity of the subject was evaluated. The test consisted of two walking efforts performed on a mechanical treadmill. The subject was walking for 12 minutes with shoe orthoses at constant speed (12 km/h) and then the rest phase allowed for the total covering of the oxygen debt. Then the trial was repeated without orthoses. Simultaneously with measuring physiological variables, there was made 3D recording of the athlete's movements on the treadmill applying the Vicon system.

There were chosen vertical oscillations of the body center of gravity and work of the subject's system of motion connected with kinetic and potential energy changes regarding the movements of COM during gait.

The energy cost of walking at speed related to anaerobic threshold (starting) using shoe orthoses was slightly lower compared to energy expenditure during gait without improvement.

No significant differences were noticed in the range of summary vertical COM oscillations during walking in both variants of the measurement. However, considerable asymmetries appeared in the value of COM kinetic energy changes that were lower for the right leg. This testifies to a strongly fixed asymmetrical scheme of individual athlete's technique.

Key words: race walking, energy cost, COM oscillations, energy changes

1. Introduction

A high level of aerobic capacity of an organism is one of the basic conditions allowing significant results in endurance competitions to be obtained. The maximum oxygen uptake, and particularly the speed of movement (running, walking, cycling, etc.) with the intensity of effort relevant to anaerobic threshold, has in this case a first-rate significance. It can happen, however, that the factors mentioned above do not differentiate competitors considerably and the results achieved by them are diametrically different. The reason for these disproportions can be explained by different energy cost of moving in a given sport competition. This indicator depends on many issues where technique of movement seems to be most important.

A detailed evaluation of both physical capacity of an organism and energy cost of effort is a fundamental task of sport physiology. However, a detailed analysis of technique is a domain of sport biomechanics. The combination of knowledge and experience gained in both fields of science and the possi-

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bility of using modern computerized measurement equipment can be difficult and may lead to the overestimation of the results in the description of the optimal technique of movement which would allow its energy cost to be minimized. Decreasing amount of energy dissipated during work is transformed directly into decreasing muscles' demand for oxygen. This causes lower contribution of anaerobic exchanges keeping the same effort intensity. The competitor, as a result, can move at higher speed using the same volume of oxygen.

Walking race is a discipline of endurance character. The assumptions mentioned above can be altered directly into the results achieved by the representatives of this sport competition. One of them is our subject, who is among the leading competitors in the world at present.

During detailed biomechanical analysis the difference in the legs' length difficult to identify by visual observation was noticed (this was confirmed later by RTG study). Such a state manifests itself as the disturbances of walking mechanics seen as asymmetry of movements – mainly in the hip joint and lumbar spine. This results, among others things, in too great oscillations of COM. On the basis of precise measurements, the difference in the length of extremities was reduced by applying made-to-measure special shoe insoles. They were used by this athlete for four weeks prior to the study of energy cost of walking.

The aim of the study was to evaluate of the influence of legs' length modification due to special shoe orthoses on the walking energy cost of the leading Polish representative in race walking.

2. Material and method

The subject of the study was one of the athletes taking part in race walking not only in Poland, but also in the world. The greatest success in his sport career was to take the seventh place in walking the distance of 50 km during the Olympic Games in Athens (2004).

Before the tests, some basic somatic parameters, i.e., height and body mass, per cent of fat, fat mass and lean body mass, of the athlete were measured.

In order to determine the aerobic capacity of the subject (the maximum oxygen uptake and the level of anaerobic threshold), a direct method was applied using walking test with gradually increased working load. The test was performed on a mechanical treadmill. During the first three minutes the subject was warming up at the speed of 8 $km \cdot h^{-1}$. Then, every three minutes, the walking speed was increased by 1 $km \cdot h^{-1}$. Previous consultations with the subject allowed us to find a reduced speed of 15 $km \cdot h^{-1}$ above which the intensity of effort was higher due to one per cent increase in the angle of moving tape fixation.

This was a result of obtaining maximum (for this athlete) walking speed, above which he would be forced to apply flight phase which means the start of running. The trial was continued until the subject felt exhaustion (he refused to continue effort). Before the test and 3 minutes after, arterialized fingertip blood sample was taken for the analysis of the rest and effort blood lactate concentration. This was accomplished by using an enzymatic method (Biomerieux tests).

Anaerobic threshold was analyzed based on the dynamics changes of the respiratory system parameters (maximum value of $FECO_2$, a significant increase in VE and minimum value of $VE \cdot VCO_2^{-1}$) [1].

Walking threshold speed, determined during gradual test, was applied during the other effort trial, being a proper part of the study. The purpose of this part of the experiment was to calculate the energy cost of walking with starting speed using the shoe orthoses matched individually as a result of the previous detailed biomechanical gait analysis with and without these orthoses.

The test consisted of two walking efforts performed on the mechanical treadmill according to the same method. After a 3-minute rest phase, the subject was walking for 12 minutes at the constant speed of 12 km/h, and then the rest phase allowed for a total covering of oxygen dept and removing shoe orthoses from his shoes. Then the procedure was precisely repeated.

During all those effort tests many parameters of the respiratory and blood systems were recorded at the intervals of 30 seconds (pulmonary ventilation, per cent of oxygen and carbon dioxide in exhaled air, pulmonary oxygen uptake and pulmonary carbon dioxide output, respiratory quotient, oxygen and carbon dioxide respiratory quotient and heart rate).

Energy cost of effort was calculated with the indirect method on the basis of oxygen netto uptake during work and directly after its completion, till the moment of total covering of oxygen dept. The magnitude of the respiratory quotient (RQ) that was used for this purpose was related to the actual proportion of the volume of carbon dioxide to oxygen uptake.

Simultaneously with the measurement of physiological variables, 3D recording of the subject's movement on the treadmill was made using Vicon system. Passive markers were stuck directly to the subject's skin at the appropriate anthropometric points of his body according to the Golem model and his gait was filmed using 5 cameras strobing the moving subject in infra-red at the frequency of 120 Hz. Both variations of the gait mentioned above were recorded. When information on anthropometric measures of the subject was introduced to the system, we achieved 3D visualization of the skeleton and the muscles chosen. Based on this information it was possible to calculate biomechanical variables characterizing walking technique at starting speed. There were chosen spatio-temporal athlete's gait parameters, spatial oscillations of COM and work of the subject's system of motion connected with kinetic and potential energy changes in the movements of COM during gait.

The subject's body parameters such as mass, per cent of fat, fat mass, and lean body mass were measured using electronic scale "Tanita" – Body Composition Analyzer – TBF-300 model of Japanese production. The body height was measured with anthropometer. All effort tests were carried out on the mechanical treadmill "Cardionics"-2113 model of Sweden production.

The parameters of respiratory system were recorded using the computerized ergospirometer "Medicro 919" made in Finland and programmed for measurement at 30 second intervals. Heart rate was analyzed using "Vantage NT" of Polar-Electro (Finland) measuring the value of this parameter at 15 minute intervals.

3. Results

In the day of the study, the subject's body mass was 64.6 kg at the body height of 177 cm. The athlete was characterized by very low fat mass (2.8 kg), i.e., was 4.3% of his total mass. Lean body mass was then 61.8 kg.

The maximum oxygen uptake achieved during graded test was 55.3 $cm^3 \cdot kg^{-1} \cdot min^{-1}$ (3.6 $dm^3 \cdot min^{-1}$) (table 1), which is surprisingly low in the representative of a typical endurance sport competition, achieving such exciting results during international competitions. VO_2max was achieved at the pulmonary ventilation of 142 $dm^3 \cdot min^{-1}$ and the heart rate of 189 $beats \cdot min^{-1}$.

The test effort lasted 26.5 min and was stopped by the subject at the speed of 15 $km \cdot h^{-1}$ (4.2 $m \cdot s^{-1}$, 250 $m \cdot min^{-1}$) and the slope angle of treadmill of 1%. In the third minute when the effort was over, blood lactate concentration was 12.7 $mmol \cdot dm^{-3}$ and was greater than the rest value (1.57 $mmol \cdot dm^{-3}$) by 11.13 $mmol \cdot dm^{-3}$.

Table 1. Physiological indices achieved during maximum effort

t	V	VO_2max	VO_2max	VEmax	HRmax	LA_{sp}	LA_{wys}	ΔLA
min	$m \cdot s^{-1}$	$cm^3 \cdot kg^{-1} \cdot min^{-1}$	$dm^3 \cdot min^{-1}$	$dm^3 \cdot min^{-1}$	$beats \cdot min^{-1}$	$mmol \cdot dm^{-3}$	$mmol \cdot dm^{-3}$	$mmol \cdot dm^{-3}$
26.5	4.2	55.3	3.6	142	189	1.57	12.7	11.13

t – time of effort, V – speed of walking, VO_2max – maximum oxygen uptake, VEmax – maximum pulmonary ventilation, HRmax – maximum heart rate, LA_{sp} – rest blood lactate concentration, LA_{wys} – blood lactate concentration 3 minutes after effort.

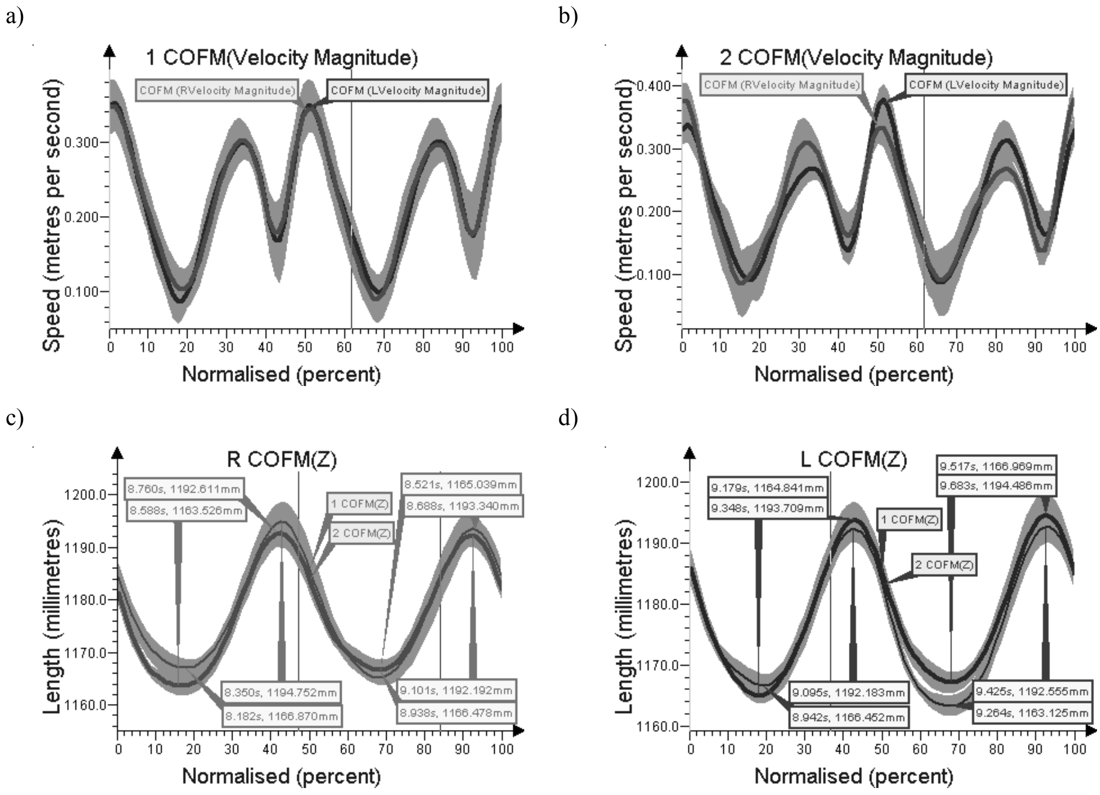
Table 2. Physiological indices achieved during effort of the intensity relevant to anaerobic threshold

t	V	VO_2	VO_2	VE	HR	$\%VO_2max$	%HRmax
min	$m \cdot s^{-1}$	$cm^3 \cdot kg^{-1} \cdot min^{-1}$	$dm^3 \cdot min^{-1}$	$dm^3 \cdot min^{-1}$	$beats \cdot min^{-1}$	%	%
12.5	3.3	43.0	2.8	68	162	77.8	85.7

An anaerobic threshold was achieved by the athlete at the oxygen uptake of 43 $cm^3 \cdot kg^{-1} \cdot min^{-1}$ (2.8 $dm^3 \cdot min^{-1}$), i.e., 77.8% VO_2max, and at the pulmonary ventilation of 68 $dm^3 \cdot min^{-1}$. The threshold heart rate was 162 $beats \cdot min^{-1}$ (85.7% HRmax). An anaerobic threshold was achieved by the subject after 12.5 min of work at relatively high walking speed of 12 $km \cdot h^{-1}$ (3.3 $m \cdot s^{-1}$, 200 $m \cdot min^{-1}$) (table 2).

The threshold gait speed achieved was applied during the main part of the study. Total oxygen netto cost of the first effort (walking at the constant speed of 12 $km \cdot h^{-1}$ with shoe orthoses) was 26.69 dm^3. Effort energy cost, calculated taking into account a right RQ, was 555.42 kJ (132.73 kcal), i.e., 46.28 $kJ \cdot min^{-1}$ (11.06 $kcal \cdot min^{-1}$) if it was calculated per 1 minute of the work. However, converting it to one gait cycle we achieved 462.2 J.

Vertical displacements of the COM as well as potential and kinetic energy transformations were calculated separately for both legs, and the values obtained corresponded to one total gait cycle (figure 1). COM



Mean values of the changes of resultant speed of COM ((a) – I study/trial, (b) – II study/trial) and vertical oscillations of COM on the background of the results in the particular walking cycle ((c) – right supportive leg, (d) – left supportive leg)

Table 3. Physiological cost, vertical oscillations of COM and the changes of potential and kinetic energy of COM calculated for gait cycle in both trials

Experiment	V	Physiological cost	Σ oscillations of COM		ΔEp		ΔEk		ΔEp + ΔEk	
	$m \cdot s^{-1}$	J	mm		J		J		J	
			R	L	R	L	R	L	R	L
Without orthoses	3.3	464.1	55.2	56.0	35.5	35.0	71.7	77.6	107.2	112.0
With orthoses	3.3	462.2	56.5	54.8	34.7	35.8	71.7	77.6	107.5	113.4

Σ oscillations of COM – total value of vertical oscillations of COM during entire gait cycle.

oscillations in the first stage of the experiment for both supportive extremities were as follows: L-25.7 mm, R-27.8 mm during take-off phase and L-29.5 mm, R-28.3 mm during swing phase. The differences were slight (no more than 0.5 cm). Total potential energy changes of COM were almost identical for both legs (L-35 J; R-35.5 J) in each gait cycle. A resultant speed of the COM was characterized by several mean hesitations, depending on the phase of a gait cycle. The corresponding total means of COM kinetic energy changes in each cycle were: L-77.6 J, R-71.7 J. The sums of the kinetic and potential energy changes were: L-112 J and R-107.2 J during each walking cycle.

The oxygen net cost of the second effort in the main part of the study, performed according to the same method but without shoe orthoses, was 26.93 dm^3. In this case, the total energy cost of work was 557.72 kJ (133.25 kcal). As far as the time of effort was taken into account, this cost was 46.5 $kJ \cdot min^{-1}$ (11.11 $kcal \cdot min^{-1}$), which gave the value of 464.1 J per each gait cycle. The expenditure of energy for the effort after removing the shoe orthoses increased by 200 $J \cdot min^{-1}$ (48 $cal \cdot min^{-1}$).

In the second study, the COM oscillations for both supportive extremities were as follows: L-28.9 mm, R-29.1 mm in take-off phase and L-27.6 mm, R-25.7 mm in swing phase. This time, more significant differences were observed in the right leg; however, they were also slight, i.e., 3 mm. Total potential energy changes of COM being calculated for both athlete's legs reached the following values: L-35.8 J, R-34.7 J in each walking cycle. Total means of kinetic energy changes of COM in each walking cycle were: L-77.6 J, R-71.7 J. The sums of the changes of COM potential and kinetic energy were equal to: L-113.4 J and R-107.5 J in each walking cycle (table 3).

4. Discussion

Walking race is a discipline of endurance character, that is why it requires not only a right technique, but also high level of aerobic capacity where maximum minute oxygen uptake is its gauge [2].

The results achieved by our subject seem to contradict this thesis. His VO_2max equal to 55.3 $cm^3 \cdot kg^{-1} \cdot min^{-1}$ is not high compared to other representatives of endurance sport competitions. The best running skiers all over the world achieve, e.g., the results above 80 $cm^3 \cdot kg^{-1} \cdot min^{-1}$ [3]. A similar value of this parameter was achieved by a multiple gold medallist of Olympic Games in this discipline during endurance studies in the Department of Physiology and Biochemistry at the University of Physical Education in Kraków.

Despite a significantly lower aerobic capacity, our subject effectively reduced this deficit due to relatively high speed of walking with the intensity of anaerobic threshold.

This speed (12 $km \cdot h^{-1}$ (3.3 $m \cdot s^{-1}$)) of the subject and relatively high value of anaerobic threshold allow him to achieve good results not only in Poland, but also abroad during the most important international competitions, e.g., Olympic Games.

The subject's starting speed of about 12 $km \cdot h^{-1}$ (3.3 $m \cdot s^{-1}$, 200 $m \cdot min^{-1}$) is almost twice as high as that of the individually adjusted to walking not training men aged 20–59, who reached an average value of 6.4 $km \cdot h^{-1}$ (1.8 $m \cdot s^{-1}$, 106 $m \cdot min^{-1}$) [4]. At this speed of gait an average oxygen uptake in 'steady state' was 18.4 $cm^3 \cdot kg^{-1} \cdot min^{-1}$; however, the heart rate reached 124 $beats \cdot min^{-1}$ [5]. Almost two times faster walking of the Polish representative under study allowed a pulmonary oxygen uptake of about 41 $cm^3 \cdot kg^{-1} \cdot min^{-1}$ at the heart rate approaching 158 $beats \cdot min^{-1}$ in both efforts (with and without shoe insoles).

A special attention should be paid to a lower physiological energy cost of subject's gait calculated per 1 meter of the distance covered (0.17 $cm^3 \cdot kg^{-1} \cdot m^{-1}$) compared to the cost measured for men who did not practice any kind of sport and who were walking at almost two times lower speed (0.19 $cm^3 \cdot kg^{-1} \cdot m^{-1}$).

WATERS's et al. [4] studies referring to the mutual relationships between gait speed and the magnitude of energy cost led to the pattern allowing calculation of oxygen cost of walking, depending on its speed. The oxygen cost of walking calculated on the basis of the pattern proposed was slightly lower for our subject (38.5 $cm^3 \cdot kg^{-1} \cdot min^{-1}$) than those obtained during both effort tests (41.1 $cm^3 \cdot kg^{-1} \cdot min^{-1}$).

The study of energy cost during walking on the basis of the COM movement analysis was carried out by CAVAGNA and MARGARIA [6]; however, they analysed only the contact of feet with the ground, thus their results were not precise enough. WINTER [7] indicated the underestimation of energy cost because of not taking into account the swing phase and he suggested measurement on the basis of the summation of the energy of body segments.

YACK [8] and WINTER [9], in their later works, suggested to use their conversion of the cost of effort into the power generated in joints by working muscles. However, the results achieved are significantly different since they not always respect all the energetic components affecting the total energy cost of walking or running.

The results of biomechanical analysis in comparison to the results of physiological analysis carried out in this paper showed that total changes of the kinetic and potential energy referring to COM movements are merely about 25% physiological cost. The other energy transformations are due to intersegmentary passive and active energy flow, the changes of the spring energy of the muscles, and the changes of kinetic energy of rotation movement in joints [9].

Any significant differences in total vertical COM oscillations during gait with and without orthoses were not observed; however, visible asymmetry appeared in the values of COM kinetic energy changes that were considerably smaller for the right leg. In one cycle, they achieved almost 6 J, which means a significant difference of 60.6 kJ at the distance of 20 km. A slight decrease in the value of COM potential energy was observed after applying orthoses in a shorter right leg, but simultaneously the value of potential energy changes in contralateral limb insignificantly increased. This can happen in consequence of the compensation mechanism.

Our research revealed only insignificantly lower energy cost of walking with shoe orthoses, proposed as a result of a detailed biomechanical analysis, compared to the cost of walking without these orthoses. Probably the differences in kinetic energy changes can be compensated for other energy components of the biomechanical cost of walking.

The subject took part in effort trials just 4 weeks after the day when the legs' length was modified. Thus we can expect further reduction in physiological cost of work after longer period of using shoe orthoses. Nevertheless the reasons for the differences in the kinetic energy changes should be found through a detailed analysis of the movement technique.

5. Conclusions

1. A lower average oxygen capacity of the subject is compensated for his relatively high speed of walking on the level of anaerobic threshold, which allows him to achieve the fine results in international competitions.

2. The energy cost of walking at the speed related to anaerobic threshold (starting) using shoe orthoses was slightly lower compared to the energy expenditure during gait without this improvement.

3. Slight differences in energy cost of walking with/or without shoe orthoses do not allow us to explicitly state whether or not the procedure described can significantly affect the subject's results.

4. No significant differences were observed in the total vertical COM oscillations during walking in both variants of the measurements. However, considerable asymmetries appeared in the value of COM kinetic energy changes that were slighter for the right leg. This testifies to a strongly fixed asymmetrical scheme of individual athlete's technique.

5. The lengthening of the training period with the usage of shoe orthoses from one to several months can affect further decrease in walking energy cost because of a better adjustment of motion system to new length proportions within lower extremities.

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