Index of mechanical work
in gait of children with cerebral palsy

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The pathological gait of children with cerebral palsy involves higher mechanical work, which limits their ability to function properly in society. Mechanical work is directly related to walking speed and, although a number of studies have been carried out in this field, few of them analysed the effect of the speed. The study aimed to develop standards for mechanical work during gait of children with cerebral palsy depending on the walking speed.

The study covered 18 children with cerebral palsy and 14 healthy children. The BTS Smart software and the author's software were used to evaluate mechanical work, kinetic, potential and rotational energy connected with motion of the children body during walk.

Compared to healthy subjects, mechanical work in children with cerebral palsy increases with the degree of disability. It can be expressed as a linear function of walking speed and shows strong and statistically significant correlations with walking gait. A negative statistically significant correlation between the degree of disability and walking speed can be observed. The highest contribution to the total mechanical energy during gait is from mechanical energy of the feet. Instantaneous value of rotational energy is 700 times lower than the instantaneous mechanical energy. An increase in walking speed causes the increase in the effect of the index of kinetic energy on total mechanical work.

The method described can provide an objective supplementation for doctors and physical therapists to perform a simple and immediate diagnosis without much technical knowledge.

Key words: *children walking, cerebral palsy, mechanical energy*

1. Introduction

The number of children born with cerebral palsy (CP) in recent 40 years has risen to over 2 per 1,000 births [13]. Pathological gait limits opportunities of CP children to properly exist in society and involves increased energy expenditure. Therefore, minimization of energy expenditure represents an important factor in rehabilitation. In order to obtain best possible results of treatment, contemporary rehabilitation of children with cerebral palsy is based on cooperation of the doctors from various fields of specialization, including physical therapists, gait analysts, surgeons, neurosurgeons, and orthopaedic surgeons.

Energy expenditure is typically divided into metabolic and mechanical while researchers are constantly searching for the relationships between these two types. Regardless of the measurement method used, total mechanical work is not synonymous with total consumption of energy [2], but its measurement is useful due to the availability of the equipment in most laboratories that analyse gait cycle [20]. Low level of correlation exists between mechanical work and the expenditure calculated using the oxygen method [11]. Regardless of the model used, mechanical energy is higher in children with CP [22]. To the previous four conditions of proper gait determined by Perry [16], Gage [5] added the energy expenditure as a determinant that results from meeting the latter four conditions. Few publications have discussed the relation-

ships between kinematic parameters during walk and speed [19], but no relationships that describe mechanical work in the gait of children with cerebral palsy and walking speed have been evaluated. The efficient and objective methods of evaluation of the motor aspects and progress in treatment are being developed. The most popular classification used worldwide is Gross Motor Function Classification System (GMFCS), which is qualitative and subjective classification of children with cerebral palsy [15]. The classification divides children with cerebral palsy into six degrees, with higher degrees corresponding to lower motor abilities of children. The degrees I to III are used to denote a child who walks unaided, with the help of an adult, walking frame or crutches, whereas the degrees IV to VI denote children who have to use wheelchairs or be moved by other people. The system is mainly based on a subjective classification of the doctors and physical therapists concerning the evaluation of the unaided moving with particular emphasis on sitting and standing positions (control of the body) and walking. The demand for simple, objective and quantitative methods of evaluation of gait efficiency and progresses in rehabilitation of the disabled children is enormous. Qualitative information does not always reflect the actual motor status of the child who is usually nervous during the examination, which negatively affects the results. Therefore, future rehabilitation might be inadequate. Furthermore, qualitative evaluation is time-consuming and the description of the disorder is subjective. Gait analysis that uses modern biomechanical techniques is a reliable tool for clinical evaluation of locomotion of children with cerebral palsy. The study presents the results of long-term studies in the group of children with cerebral palsy with division into degrees on the GMFCS scale with respect to walking speed. The aim of the study is to determine the standards for mechanical work in children with cerebral palsy walking unaided, classified at three levels of the GMFCS scale, depending on the walking speed.

2. The children studied

The study design was approved by the Senate's Research Bioethics Committee. Parents and guardians were familiarized with the procedures used and signed the informed consent for the experiments. The study evaluated eighteen children with cerebral palsy that attended the Rehabilitation and Neuropsychiatric Centre in Mikoszów and fourteen healthy children at the age of 7. The subjects were examined 4 to 7 times from September 2007 to September 2010. The healthy children were examined once, in April 2010. The children with cerebral palsy underwent treatment administered by the physician, supplemented with the therapy that used Mechanical Home Pony [4]. Mean age, speed, body mass and height, and length of lower limbs of the children with standard deviation are presented in Table 1A. The criterion for inclusion of 7 children into the group of healthy subjects was maturity of the gait at this age [23]. The age of children with cerebral palsy varied. The youngest child was 8, whereas the oldest one was 16 years old. The group of children with cerebral palsy could be so varied since the chronological age in these children differs from their functional age, determined using GMFCS criteria [15]. Children with cerebral palsy were examined and diagnosed by a neurologist and assigned to three functional levels according to GMFCS. Before the examination proper, the child was familiarized with the apparatus and the room. Children were wearing only underpants (the room temperature was 20° to 22 °C).

3. Measurement methodology

Walking tests were carried out in the Biomechanical Laboratory (with PN-EN ISO 9001:2009 Quality Management System certification). BTS Smart software with 6 infrared cameras that recorded the motion at the frequency of $f = 120$ Hz and advanced to the upper limbs Davis model [23] were used to determine the centres of gravity of body segments. The measurement path went through the central point of the laboratory, with children walking barefoot along the path. The length of the section covered by children was 12 m, which involved 10–12 full walking cycles. This length of the testing path ensured the acceleration to the most comfortable speed and breaking. The child walked along the testing path at least 10 times. Some children needed more time and more attempts to complete the whole section in a natural walking manner, which resulted from the problems with locomotion and adjustment to the testing environment. In some cases, the test was repeated even 20 times.

Some children with cerebral palsy walked with the walking speed similar to the speed preferred by healthy children. However, the most of them walked slower (see Table 1A) [19]. At least 6 properly recorded walks were used during analysis, of which each walk comprised 4 to 8 correct gait cycles. A gait

cycle encompassed the time from the very first contact of the right foot with the ground until the next contact of the same foot with the ground.

Calculation procedure

Mechanical work *Wt* and indices of kinetic and potential energy *Wk* and *Wp* were calculated based on the author's software that calculates this parameter according to the following stages:

1. Finding masses (m_j [kg]), radius vectors for the centres of gravity (r_j [m]) and radii of gyration (R_j [m]) for 12 body segments ($j = 1, ..., 12$) on the right (Right) and left (Left): foot (f), calf (c), thigh (th), arm (a), forearm (fa), trunk (tr) and head (h) by means of regression equations according to Jensen [8], using the Davis model extended with upper limbs and the method and BTS Smart software.

2. Determination of the central moments of inertia I_j [kgm^2] for 12 ($j = 1, ..., 12$) segments in the child's body in the frontal plane (f) and the sagittal plane (s) according to the equation

$$I_j = \frac{m_j R_j^2}{2}. \qquad (1)$$

3. For each child's body segment *j*, the instantaneous ($i = 1$ ... number of samples), normalized (with respect to body mass *M* [kg] and body height *H* [m]) values of potential energy connected with the work performed with the gravity force ($Ep_{y,i,j}$) and kinetic energy ($Ek_{i,j}$) of the translational motion *x*, *y*, *z* and energy of rotational motion ($Eo_{i,j}$) in the sagittal plane (s) and the frontal plane (c) according to the recommendations of Hof [7] and equations (2) to (9) for individual walks performed by the child were determined.

$$Ep_{y,i,j} = \frac{g \cdot y_{i,j}}{H}, \qquad (2)$$

$$\Delta t = \frac{1}{f} = \frac{1}{120}, \qquad (3)$$

$$Ek_{x,i,j} = \frac{v_{x,i,j}^2}{2H}, \quad v_{x,i,j} = \frac{\Delta x_{i,j}}{\Delta t} = 120 \cdot \Delta x_{i,j}, \qquad (4)$$

$$Ek_{y,i,j} = \frac{v_{y,i,j}^2}{2H}, \quad v_{y,i,j} = \frac{\Delta y_{i,j}}{\Delta t} = 120 \cdot \Delta y_{i,j}, \qquad (5)$$

$$Ek_{z,i,j} = \frac{v_{z,i,j}^2}{2H}, \quad v_{z,i,j} = \frac{\Delta z_{i,j}}{\Delta t} = 120 \cdot \Delta z_{i,j}, \qquad (6)$$

$$Ek_{i,j} = Ek_{x,i,j} + Ek_{y,i,j} + Ek_{z,i,j}, \qquad (7)$$

$$Eo_{c,i,j} = \frac{I_{c,j}\omega_{c,i,j}^2}{2MH}, \quad \omega_{c,i,j} = \frac{\Delta\alpha_{c,i,j}}{\Delta t} = 120 \cdot \Delta\alpha_{c,i,j}, \qquad (8)$$

$$Eo_{s,i,j} = \frac{I_{s,j}\omega_{s,i,j}^2}{2MH}, \quad \omega_{s,i,j} = \frac{\Delta\alpha_{s,i,j}}{\Delta t} = 120 \cdot \Delta\alpha_{s,i,j}, \qquad (9)$$

i – sample number, $i = 1, ..., n$,

j – segment number, $j = 1, ..., 12$,

$x_{i,j}$ [m] – instantaneous location of the centre of gravity COG of the segment *j* on the axis *x* (horizontal) along the child's transverse body axis,

$y_{i,j}$ [m] – instantaneous location of the centre of gravity COG of the segment *j* on the axis *y* (vertical) along the child's long body axis,

$z_{i,j}$ [m] – instantaneous location of the centre of gravity COG of the segment *j* on the axis *z* (horizontal) along the child's sagittal axis,

$v_{i,j}$ [m/s] – instantaneous linear velocity of the centre of gravity (COG) of the segment *j* on the axis *x*, *y*, *z*,

$\alpha_{c,i,j}$ [rad/s] – instantaneous angular location of the segment *j* measured as the angle between the projection of the section connecting the beginning and the end of the segment *j* on the frontal plane *c* and the horizontal plane of the system of reference,

$\alpha_{s,i,j}$ [rad/s] – instantaneous angular location of the segment *j* measured as the angle between the projection of the section connecting the beginning and the end of the segment *j* on the sagittal plane *s* and the horizontal plane of the system of reference,

$\omega_{i,j}$ [rad/s] – instantaneous angular velocity of the segment *j* in the sagittal plane *s* and the frontal plane *c*,

g [m/s^2] – gravitational acceleration ($g = 9.81$ m/s^2),

H [m] – child's body height,

M [kg] – child's body mass,

I_j [kgm^2] – central moment of inertia for the segment *j* in the sagittal plane *s* and the frontal plane *c*,

$Ep_{y,i,j}$ [ND] – instantaneous value of potential energy of the gravity force for the segment *j*,

$Ek_{x,i,j}$ [ND] – instantaneous value of the kinetic energy connected with the forward motion *j*,

$Ek_{y,i,j}$ [ND] – instantaneous value of the kinetic energy connected with the vertical motion of the segment *j*,

$Ek_{z,i,j}$ [ND] – instantaneous value of the kinetic energy connected with the lateral motion of the segment *j*,

$Eo_{s,i,j}$ [ND] – instantaneous value of the rotational energy connected with the motion of the segment *j* in the sagittal plane,

$Eo_{c,i,j}$ [ND] – instantaneous value of the rotational energy connected with the motion of the segment *j* in the frontal plane.

4. For each walk performed by a child, calculation of the mean energy over one cycle of walk *Enp*, *Enk* and *Eno* with standard deviation SD for normalized time of the gait cycle (1 total cycle = 100%) for child's body segments. The energy over one cycle of work determined in the above procedure can be compared for different children since it is determined in the same cycle where the beginning and the end is the first contact of the right foot with the ground. In the following, the term cycle energy will be used.

5. Calibration of the profiles of mean cycle energy by moving them with the vector of minimum value of energy to zero *Ep0*, *Ek0* and *Eo0* for the right and left side of each segment of child's body.

6. Calculation of instantaneous values of mean energy cycle with standard deviation SD for all walks in a child's examination mEp_i, mEk_i and mEo_i for the right and left side for each body segment.

7. Determination of the instantaneous values of total mechanical cycle energy *Et* for the whole body and each segment of child's body.

$$mEt_i = mEp_i + mEk_i + mEo_i. \qquad (10)$$

8. A dimensionless mechanical cycle work *Wt* and dimensionless indices of kinetic cycle energy *Wk*, potential cycle energy *Wp* and rotational cycle energy *Wo* were calculated for individual child's body segments using the formula

$$W = \sum_{i=1}^{100} ABS(mE_{i+1} - mE_i). \qquad (11)$$

4. Results

Using the software described in the study, the mechanical cycle work *Wt*, index of kinetic energy *Wk*,

Table 1. Characterization of the children participating in the study. I, II, III – degrees of the GMFCS scale. Relationships between the mechanical cycle work Wt, indices of cycle work and cycle energy in children with cerebral palsy and healthy subjects

A. Mean age (A), walking speed (v), mass (m), body height (H), lower limb length (ll) with standard deviation (SD) in healthy children and the children with CP					
Examination	**A ± SD [years]**	**v ± SD [m/s]**	**m ± SD [kg]**	**H ± SD [m]**	**ll ± SD [m]**
Healthy children	6.95 ± 0.31	1.07 ± 0.19	24.94 ± 4.45	1.24 ± 0.04	0.63 ± 0.03
I	14.07 ± 2.40	1.25 ± 0.24	49.17 ± 17.72	1.51 ± 0.17	0.78 ± 0.09
II	12.47 ± 3.23	0.79 ± 0.18	36.87 ± 10.74	1.46 ± 0.16	0.78 ± 0.10
III	9.53 ± 2.90	0.49 ± 0.22	30.09 ± 17.61	1.28 ± 0.24	0.67 ± 0.16

B. Correlation between walking speed v [m/s] and the mechanical cycle work Wt or indices of mechanical cycle work W of body parts. Statistically significant results at $p < 0.05$. r – right part of the body l – left part of the body f – foot, c – calf, th – thigh, a – arm, fa – forearm, h – head, tr – trunk												
	Wt	**Wrf**	**Wlf**	**Wrc**	**Wlc**	**Wrth**	**Wlth**	**Wra**	**Wla**	**Wrfa**	**Wlfa**	**Wh**	**Wtr**
Healthy children	0.95*	0.91*	0.95*	0.95*	0.96*	0.96*	0.96*	0.94*	0.84*	0.93*	0.96*	0.91*	0.93*
I	0.93*	0.88*	0.98*	0.98*	0.96*	0.93*	0.88*	0.93	0.96*	0.96*	0.96*	0.65*	0.81*
II	0.91*	0.86*	0.88*	0.92*	0.93*	0.68*	0.79*	0.74*	0.73*	0.64*	0.74*	0.70*	0.73*
III	0.94*	0.95*	0.93*	0.97*	0.98*	0.91*	0.96*	0.90*	0.76*	0.84*	0.73*	0.93*	0.93*

C. Dependence of mechanical cycle work W performed by the feet (f), calf (c) and thigh (th) on child's walking speed v[m/s]			
	Wf	**Wc**	**Wt**
Healthy children	−0.43 + 1.19v	−0.07 + 0.45v	−0.05 + 0.24v
I	−0.57 + 1.30v	−0.33 + 0.69v	−0.16 + 0.34v
II	−0.33 + 1.28v	−0.22 + 0.66v	−0.07 + 0.28v
III	−0.49 + 1.67v	−0.25 + 0.76v	−0.06 + 0.28v

D. Mean coefficient of mechanical cycle work W for individual body segments with standard deviation (SD) in healthy children and children with cerebral palsy. Mean speed indicated in the table as position A.				
	Healthy children	**I**	**II**	**III**
Wt	2.16 ± 0.62	2.55 ± 0.53	1.85 ± 0.3	1.35 ± 0.12
Wf	0.89 ± 0.23	1.13 ± 0.31	0.70 ± 0.01	0.58 ± 0.04
Wc	0.41 ± 0.12	0.55 ± 0.13	0.35 ± 0.01	0.26 ± 0.05
Wth	0.21 ± 0.07	0.27 ± 0.07	0.16 ± 0.01	0.11 ± 0.01
Wa	0.22 ± 0.06	0.36 ± 0.07	0.21 ± 0.01	0.16 ± 0.02
Wfa	0.19 + 0.3	0.34 ± 0.08	0.19 ± 0.01	0.14 ± 0.02
Wh	0.18 ± 0.02	0.22 ± 0.04	0.15 ± 0.01	0.11 ± 0.02
Wt	0.19 ± 0.03	0.26 ± 0.05	0.15 ± 0.01	0.10 ± 0.01

potential energy Wp and rotational energy Wo for all the child's body segments were computed. The study demonstrated the relationships between the mechanical cycle work and walking speed of the children studied which, if arranged as a specific algorithm, might supplement GMFCS functional gait classification (Table 1):

1. Contribution of mechanical cycle energy of body segments in total mechanical cycle energy during child's gait

The highest contribution to total mechanical cycle energy during walking is from mechanical cycle energy of the feet $(26.0 \pm 3.5)\%$, followed by the cycle energy of the calves $(18.7 \pm 2.1)\%$, forearms $(18.5 \pm 3.5)\%$, arms $(15.1 \pm 2.1)\%$ and thighs $(13.6 \pm 1.0)\%$, whereas the lowest effect is from trunk $(6.1 \pm 0.9)\%$ and head $(6.3 \pm 1.1)\%$.

The function of unit mechanical energy Et with respect to time in the case of each child has 4 extremes (2 minimums and two maximums). The minimum occurs at the heel contact, whereas the maximum is observed in the central part of the swing phase. The higher the speed, the higher instantaneous values of energy and the scope of its changes (Fig. 1). The same relationships occur in the case of mechanical energies of individual body segments (Figs. 2 and 3).
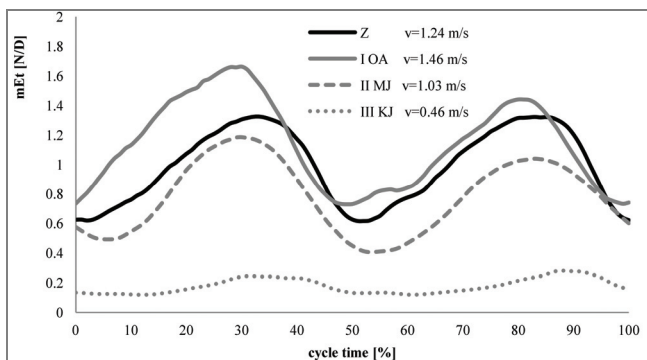
2. Relationships between walking speed and the mechanical cycle work performed by the whole body and its individual segments

Mechanical cycle work Wt of the whole body and body segments in healthy children and disabled children can be expressed as a linear function of the walking speed (Fig. 4, Table 1C). It shows a strong and statistically significant correlations with the walking speed, $p < 0.05$ (Table 1B).

3. Relationships between walking speed and the degree on the GMFCS functional scale

A negative statistically significant correlation occurs between GMFCS level and walking speed ($p < 0.05$, $r = -0.84$). Children from class I walk with the convenient speed similar to healthy children at the age of 7, with some of them moving even faster. These children are characterized by insignificant damage to motor organ and good overall functional status.

4. Energy of rotational motion. Instantaneous values of rotational cycle energy Eo_i are on average 700 times lower than the instantaneous mechanical cycle energy Et_i. Index of cycle energy connected with the rotational motion Wo is insignificant and amounts to $0.4 \pm 0.1\%$ of unit mechanical work Wt. Therefore, the rotational energy will be included in the total mechanical cycle energy. However, it will not be described in the analysis.
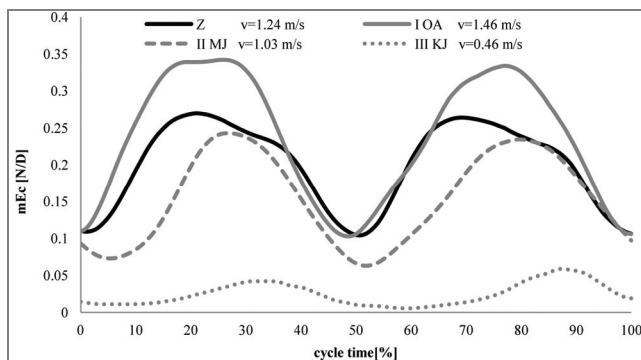

Fig. 1. Changes in mean mechanical energy mEt during a single gait cycle for healthy children (Z) and children with cerebral palsy walking at different speeds

Fig. 2. Changes in mean mechanical energy for calves mEc during a single gait cycle for healthy children (Z) and children with cerebral palsy walking at different speeds
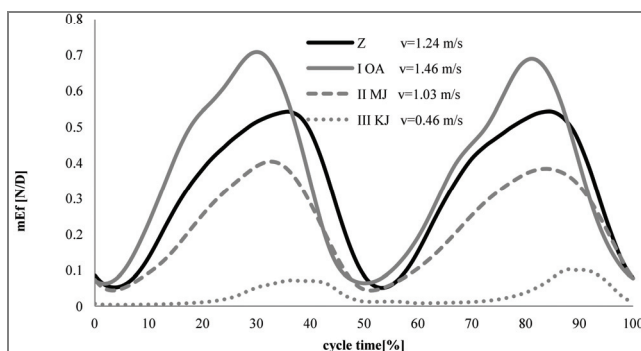

Fig. 3. Changes in mean mechanical energy for feet mEf during a single gait cycle for healthy children (Z) and children with cerebral palsy walking at different speeds

5. The effect of walking speed on proportions of indices of unit kinetic and potential energy

The increase of walking speed (v) causes an increase in the effect of the index of kinetic cycle energy Wk with respect to the index of potential cycle energy *Wp* on total mechanical cycle work, which can be expressed with the equation $Wk/Wp = -0.3164 + 3.4678v$, (Fig. 5).

6. The effect of walk velocity on the indices of kinetic and potential cycle energy

Index of potential cycle energy (Fig. 6) for healthy children and the children from group I changes
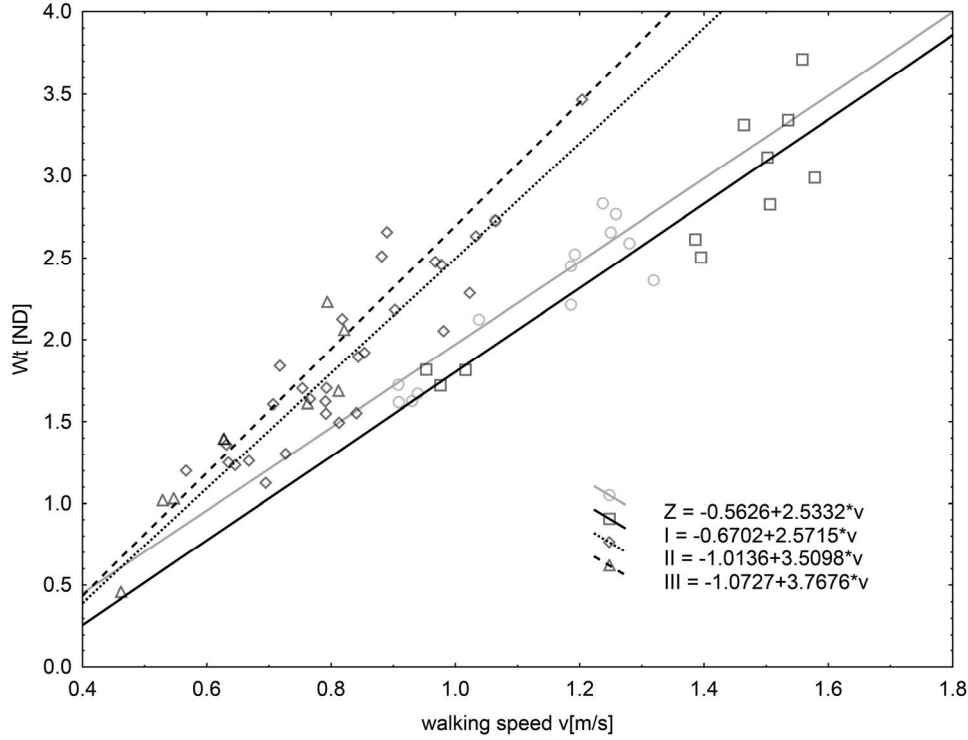

Fig. 4. Mechanical cycle work *Wt* of the child's body expressed as a linear function of the walking speed
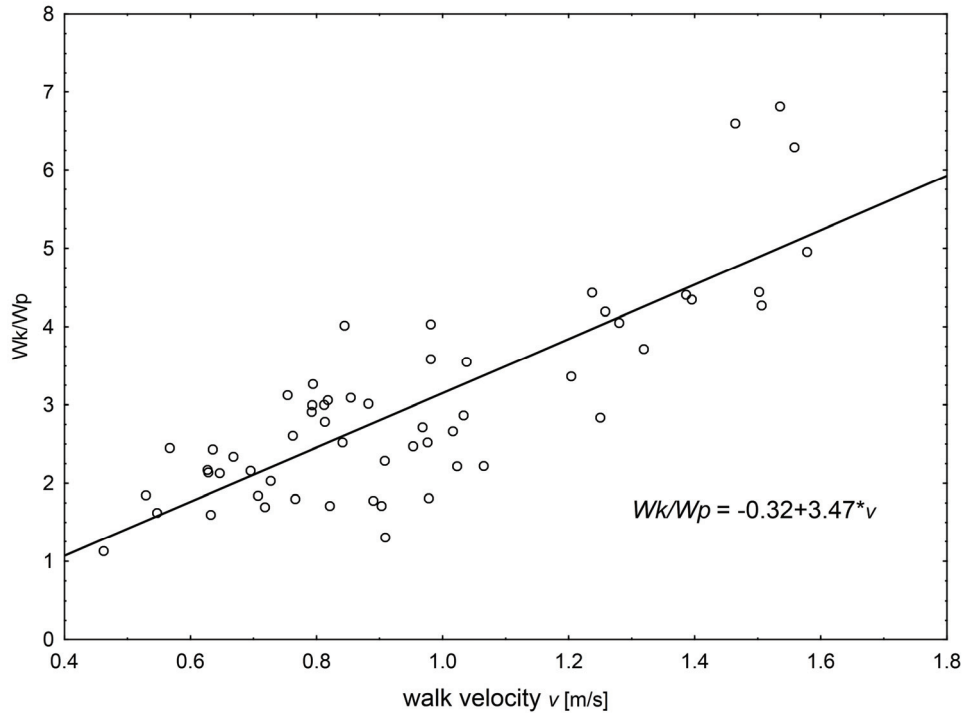

Fig. 5. The dependence of the proportion of the index of cycle kinetic energy W_k and potential cycle energy W_p expressed as a linear function of the walking speed
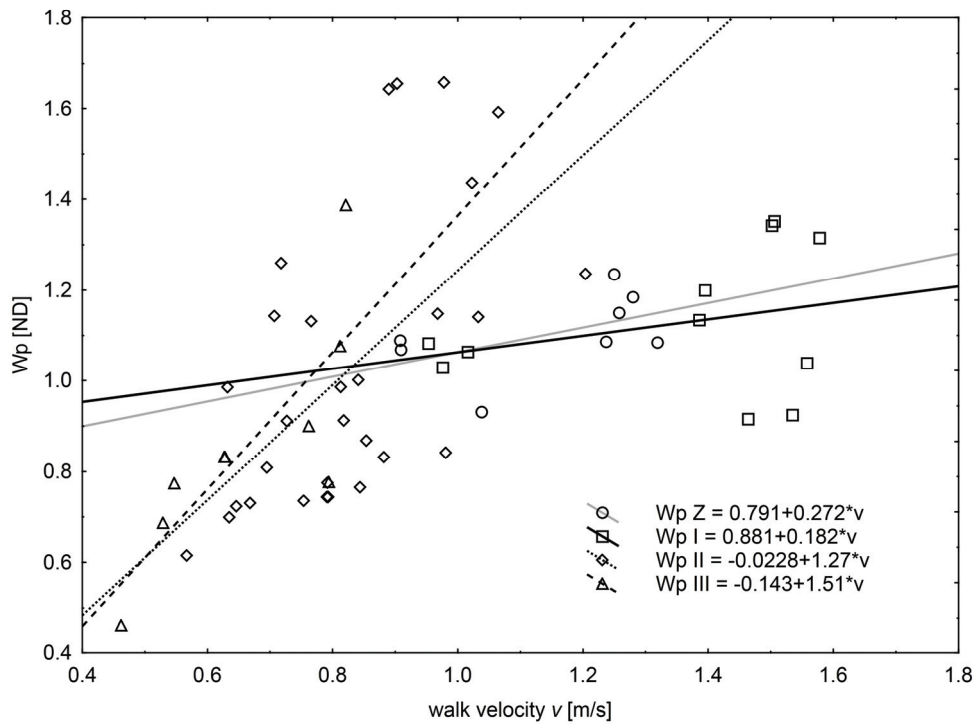
Fig. 6. The dependence of the index of potential cycle energy W_p expressed as a linear function of the walking speed
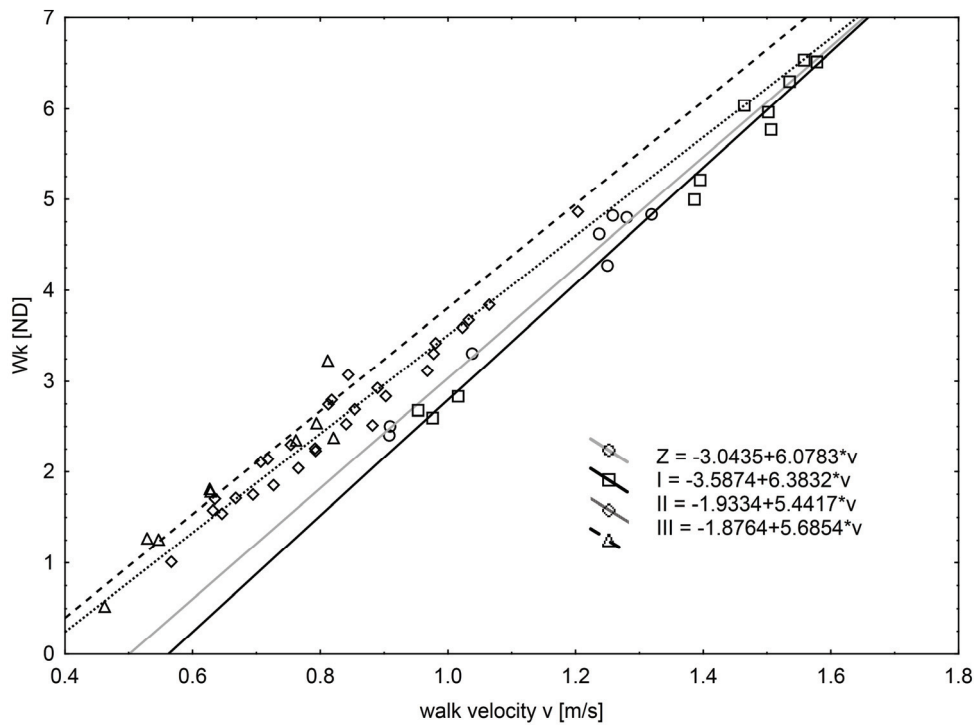

Fig. 7. The dependence of the index of kinetic cycle energy W_k expressed as a linear function of the walking speed

insignificantly with the speed, which means that the healthy children increase the speed without the increase in the range of vertical displacements of the centres of gravity. With the increase in the walking speed, more disabled children (from levels II and III), increase their range of vertical displacements of the centres of gravity of body segments.

Index of kinetic cycle energy increases in proportion to walking speed in all the children to a similar manner. However, it is higher in more disabled children.

7. The ratio of mechanical cycle work Wt performed by feet (f), calves (c) and thighs (t) during walking of children with cerebral palsy at level I, II and III to mechanical cycle work performed by these segments during walking of healthy children (walking speed of 1 m/s)

In order to determine the differences in the total cycle work performed by individual segments of lower limbs, the index I_{seg} (Fig. 8) was calculated. The index determines the ratio of the total cycle work performed by the segments of lower limbs during walking of children with cerebral palsy expressed as a percentage of total cycle work performed by individual segments in healthy children, with the walking speed of all the children $v = 1$ m/s. This index for the segments of lower limb in healthy children and those from level I is close to 100%, which means that children walk similarly. In the case of children from level II and III, the index I_{seg} is higher than 100% and the highest in the case of thighs. Children from level II and III have strong contractures of lower limbs, which limits their range of motion in the knee and hip joints and the synergy of ankle, knee and hip joints is limited. Therefore, the flow of energy between the segments and the synergy of the joints is poorer.
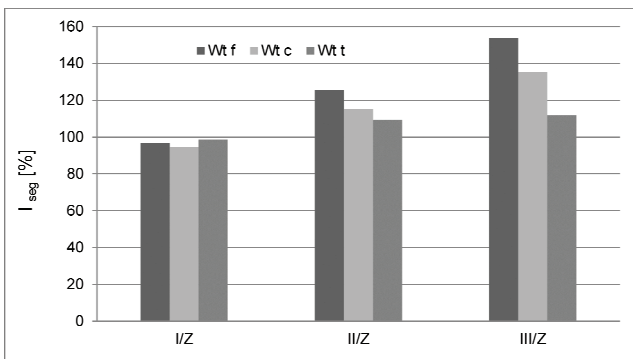

Fig. 8. The index I_{seg} that determines the ratio of the total cycle work performed by the segments (*Wtf* – feet, *Wtc* – calves, *Wtt* – thighs) of lower limbs during walking of children with cerebral palsy at levels I, II and III expressed as percentage of total cycle work done by individual segments of healthy children (Z) at the walking speed in all children $v = 1$ m/s

8. Ratio of total mechanical cycle work Wt and indices of kinetic cycle energy Wk and potential cycle energy Ep during walking of children from levels I, II, III to these parameters in healthy children at the walking speed of 1 m/s

In order to supplement information about the mechanical work done, the index I_w was calculated. The index determines the ratio of total mechanical cycle work *Wt* (or, analogically, the index of kinetic or potential cycle energy) during gait of children with cere-

bral palsy at levels I, II and III expressed as percentage of total mechanical cycle work *Wt* (or, analogically, the index of kinetic or potential cycle energy) during walking of healthy children assuming that all the children walk at the speed of 1 m/s. Children with light disability (level I) walk so that the mechanical cycle work and the indices of kinetic and potential cycle energy are similar to these parameters in healthy children. In children with higher degree of disability from levels II and III, the mechanical cycle work and indices of cycle energy are higher than in healthy children by 17 to 37% (Fig. 9).
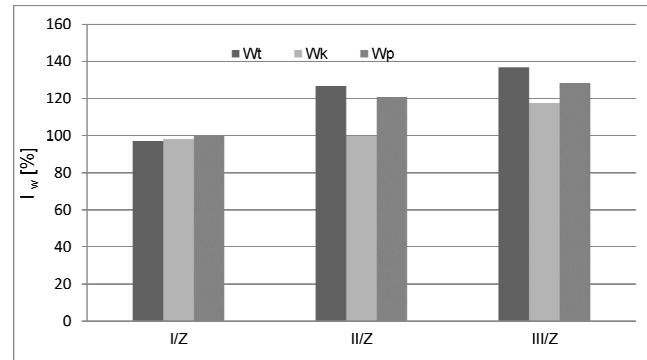

Fig. 9. The index I_w which determines the ratio of total mechanical cycle work *Wt* (or, analogically, the index of kinetic or potential cycle energy) during gait of children with cerebral palsy at levels I, II and III expressed as percentage of total mechanical cycle work *Wt* (or, analogically, the index of kinetic or potential cycle energy) during walking of healthy children assuming that all the children walk at the speed of 1 m/s

5. Discussion

According to [17], children with cerebral palsy consume 2 to 3 times more mechanical energy during gait compared to the healthy children. This statement is too general since the study demonstrated that the disabled children perform higher unit mechanical work but it depends on the degree of disability and walking speed. The economic criterion for the gait was described by Saunders et al. [18], who separated gait determinants, three movements related to the pelvis, flexion in the hip and knee joint in the support phase and synergy of the foot and knee joint. Disturbance in any of the above determinants causes a disturbance in oscillation of the overall centre of gravity and the relatively constant walking speed. The lack of one of them (with the exception of the knee joint) does not cause a substantial increase in the energy, whereas the loss of two in six determinants involves a three-time increase in this cost. This study confirms

the assumptions made by Saunders who argued that stronger muscular contractures observed in children are related to higher functional level and, consequently, higher mechanical work. A strong correlation (0.87, $p < 0.01$) between the metabolic cost in the gait of children with cerebral palsy and the GMFCS level was demonstrated [9]. The characteristics that differentiate between individual levels of the scale include the degree of disability, strength, contractures, spasticity and ineffective transfer of energy between body segments [9]. Muscular contractures of lower limbs are the main factor in increased mechanical work in children with cerebral palsy [21].

Stronger contractures connected with higher degree of functional GMFCS disability caused higher values of mechanical work. Children from group III in this study, who had the strongest contractures of lower limbs, the slowest range of motion in the ankle, knee and hip joints, had the highest unit mechanical work of the whole body and individual segments and walked at the lowest speeds. Limited mobility in the joints deteriorates synergy of the joints and decreases the exchange of energy between the segments. All the children studied walked with the preferred speed and step frequency. This is closely related to maintaining energy expenditure at the optimum level [25].

Orthoses and prostheses who replace the lost functions of the muscles or reduce deformation of the joints of lower limbs might improve the efficiency of the gait and the related energy costs [3], [24]. With age, the metabolic expenditure per body mass kilogram of a child increases [24]. Oxygen consumption per metre [ml/m] is connected with the degree of patient's disability, whereas the speed of oxygen consumption [ml/s] points to the physiological exercise during walking at the particular speed [24]. Therefore, higher index of potential cycle energy found in a child's limb segment might represent an indication for an orthopaedist to prescribe an orthosis. The disabled people who walk unaided, move at lower speeds than the healthy subjects. However, in the case of the children studied who had muscular contractures of lower limbs, limitations in hip, knee and ankle joints, a reduction in the walking speed occurs with the increase in mechanical work *Wt*. Similar relationships with respect to the metabolic expenditure were observed by Waters and Mulroy [24].

The contribution of mechanical energy with exchange of energy between segments amounts to 87.2% of metabolic expenditure of the children with cerebral palsy walking at the speed of 0.83 m/s. Increase in the mechanical energy in children with cerebral palsy was explained by Olney [14] with poor exchange of energy between segments. The studies of this author were incomplete since they concerned 2D analysis. Onley [14] argues that, if the costs of energy are considered, treatment of the disabled should be oriented at re-creation of the sinusoidal motion of the segments at minimum speed of the upper body in the mid stance phase (MSt) and maximum speed in the phase of heel contact.

Grabowski [6] demonstrated that 45–50% of the energy expenditure during walking is from lifting the COG. Mechanical and metabolic energy cost connected with the work of the muscles is substantial not only through redirecting the COG during the double support phase and lifting of the COG during the single support phase [12]. Healthy people roll the heel at the first contact with the ground (Load Response, LR) and, using the principle of the conservation of momentum, move the COG up and forward, whereas in children with cerebral palsy, the COG in LR is lowered and the first contact of the foot with the ground occurs at the forefoot, with knee and ankle joints bent. Bradford [1] wrote that children with cerebral palsy, in order to lift the COG to the maximum height during the MSt phase, must first generate the kinetic energy at the phase of foot swing since the range of motion in their knee joint is limited. Therefore, the disabled children perform more mechanical work. The amplitude in the sagittal plane of the ankle joint at the toe-off in the support phase determines the vertical displacement of the COG in patients after surgery of the pes equinus [10]. In a study by Gradford, children with cerebral palsy had by 33% poorer coefficient of energy recovery compared to their healthy peers. Their gait showed by 60% higher vertical deviations in the COG and poorer phase relation between kinetic and potential energies, which consequently generated higher mechanical energy confirmed in this study.

McDowell [11] found low level of correlation between the mechanical work calculated based on the COG and the cost calculated using oxygen method. Regardless of the model used, mechanical energy is higher in children with cerebral palsy [22]. Therefore, it is essential that experts in biomechanics cooperate with doctors and physical therapists in all the laboratories equipped with systems of infrared motion analysis in order to determine the mechanical work done by the people with pathological gait in a simple manner. This knowledge, with the software, offers opportunities for providing the paediatricians, neurologists, orthopaedic surgeons, surgeons and physical therapists with conditions for a simple and immediate diagnosis that does not require much technical expertise. For the orthopaedic surgeons, the method should

help indicate the surgical interventions and monitoring of the following treatment and the use of orthoses and observation of this type of treatment.

6. Conclusions

This study evaluated, without changing the natural walking speed, a mechanical cycle work and the indices of potential and kinetic cycle energy during gait of healthy children and the children with cerebral palsy. Mechanical cycle energy and mechanical cycle work in children with cerebral palsy differs from the values recorded for healthy subjects. It increases with the degree of disability. Mechanical cycle work depends on the walking speed and can be expresses as a linear function of the walking speed. It shows strong and statistically significant correlations with walking speed. A negative statistically significant correlation between the GMFCS scale and walking speed can be observed.

The highest contribution to the total mechanical cycle energy during gait is from mechanical cycle energy of the feet, thighs and hips. Instantaneous value of rotational energy is on average 700 times lower than the instantaneous mechanical energy. The increase of velocity in walk (v) causes an increase in the index of kinetic cycle energy with respect to the index of potential cycle energy on total mechanical cycle work. Index of potential cycle energy in healthy children and the children group I changes insignificantly with the increase in speed, whereas it changes substantially in children from levels II an III. Index of kinetic cycle energy increases in proportion to walking speed in all the children to a similar manner. However, it is higher in more disabled children. The index I_{seg} that determines the ratio of the total cycle work performed by the segments of lower limbs during walking of children with cerebral palsy expressed as percentage of total cycle work done by individual segments of healthy children at the walking speed in all children $v = 1$ m/s is higher than 100% in children from level II and III, the highest in the case of feet and the lowest for thighs. The index I_w which determines the ratio of total mechanical cycle work (or, analogically, the index of kinetic or potential cycle energy) during gait of children with cerebral palsy at levels I, II and III expressed as percentage of total mechanical cycle work (or, analogically, the index of kinetic or potential cycle energy) during walking of healthy children assuming that all the children walk at the speed of 1 m/s is higher than 100% in children with the degree of disability at level II and III.

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