Mechanical energy estimation during walking: Validity and sensitivity in typical gait and in children with cerebral palsy

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ABSTRACT

Gait efficiency in children with cerebral palsy is usually quantified by metabolic energy expenditure. Mechanical energy estimations, however, can be a valuable supplement as they can be assessed during gait analysis and plotted over the gait cycle, thus revealing information on timing and sources of increases in energy expenditure. Unfortunately, little information on validity and sensitivity exists.

Three mechanical estimation approaches: (1) centre of mass (CoM) approach, (2) sum of segmental energies (SSE) approach and (3) integrated joint power approach, were validated against oxygen consumption and each other. Sensitivity was assessed in typical gait and in children with diplegia. CoM approach underestimated total energy expenditure and showed poor sensitivity. SSE approach overestimated energy expenditure and showed acceptable sensitivity. Validity and sensitivity were best in the integrated joint power approach. This method is therefore preferred for mechanical energy estimation in children with diplegia. However, mechanical energy should supplement, not replace metabolic energy, as total energy expended is not captured in any mechanical approach.

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1. Introduction

In pathological gait, as in children with cerebral palsy (CP), deviations in gait pattern can lead to inefficient gait. Gait efficiency is usually quantified by assessment of energy expenditure (EE) during walking, which can be defined by different methods. The main methods are metabolic energy assessment [1,2] and calculation of mechanical energy fluctuations through mathematical estimation models during gait analysis (GA) [3,4].

Metabolic EE, which accounts for all possible sources of EE, is often seen as gold standard. However, it can only be assessed over a steady state period of walking, and therefore only detect overall EE without any specific information on causes of increased EE. The clinical use of metabolic measurements in CP is further restrained by its limited reproducibility [5,6] and high variability in pediatric typical gait [7,8]. Mechanical energy estimations could provide valuable additional information in pathological gait, as they can be plotted over the gait cycle. Furthermore, mechanical estimation does not need a steady state period and can therefore also be assessed in patients for whom walking is no longer an aerobic task. Different approaches for mechanical energy estimation exist; all based on estimation of work. Since work is only done when movement is involved, mechanical approaches underestimate actual EE, as they cannot account for isometric contractions, co-contractions or work against gravity [9].

Following mechanical energy approaches are described in the literature (Fig. 1): (1) analysis of energy changes of the centre of mass of the body (CoM) relative to the surroundings (positive external work, $W_{ext}^+$) and of the body segments relative to the CoM (positive internal work, $W_{int}^+$) where total work ($W_{tot}$) is $W_{ext}^+ + W_{int}^+$ [3,4,10]; (2) analysis of energy changes of moving body segments (sum of segmental energies, $W_{SSE}$) [11] and (3) integration of power around the joints (net joint work, $W_j$) [3]. All three approaches provide considerably different estimates of work and should be used with specific reference data [12]. The CoM-approach is most frequently used [13–17], but it is unclear...
Fig. 1. Overview of the method to quantify mechanical energy during walking: the method of mechanical energy estimation can be divided into different approaches (1–3), based on different biomechanical assumptions. Within an approach, protocol can differ depending on what data are collected (kinematic or kinetic data) and how data are processed (allowing transfer or not between segments). Approaches and protocols in italics start from kinematic data, all other approaches and protocols start from kinetics.

(1) Center of mass approach
$W_{tot}^* = W_{ext}^* + W_{int}^*$

(2) Sum of segmental energies approach
$W_{SSE} = W_j |

(3) Integrated joint powers approach
$W_j = |W_{j}\ |

Estimation of $W_{ext}^*$ from ground reaction forces

Estimation of $W_{kin}^*$ from kinematics

Estimation of $W_{ext}^*$ and $W_{int}^*$ from kinematics

Allowing no transfer between segments
(upper bound: $W_{SSE\_UB}$)

Allowing 100% transfer between segments
(lower bound: $W_{SSE\_LB}$)

whether this is indeed the best approach for evaluation of pathologic gait. For clinical use, a mechanical energy approach should be valid as well as sensitive enough to discriminate between pathological and typical gait, while showing little variation in typical adult gait.

Previous attempts of validation of mechanical approaches are scarce. Burdett et al. validated three approaches in typical adults and found high correlations between approaches when EE was expressed per second but not per meter walked [18]. Martin et al. evaluated the relationship between different approaches in adults and found low to no correlation [12]. More recently, Frost found that two segmental approaches, in typical children, were good estimators of oxygen rate on individual level, but not on group level [19]. To the best of our knowledge only one study addressed validity of mechanical EE in pathologic (spina bifida) gait and found no relation with $O_2$-cost [20].

Research on sensitivity of mechanical EE is also scarce. All three approaches are sensitive enough to detect developmental changes in typical gait [7,21]. Furthermore, McDowell et al. found that $W_{SSE}$, allowing inter-segmental transfer, was able to discriminate between levels of spina bifida [20]. Van den Hecke et al. report 1.7 times higher $W_{tot}$ for children with hemiplegia compared to typical controls [16]. Caty et al. on the other hand, found no differences in $W_{tot}$ before and after Botulinum Toxine treatment in stroke patients, whereas $O_2$-cost decreased significantly [22].

Available information on validity and sensitivity of three mechanical approaches ($W_{tot}, W_{SSE}, W_j$) in typical gait and in children with CP. Although metabolic EE is often used as gold standard [12,18], it can not serve as single criterion to validate mechanical approaches as mechanical approaches do not take into account all sources of EE and approach dependent differences in magnitude are expected. Furthermore, limited reproducibility of metabolic EE and the impact of different conversion techniques may obscure observed relations. Nevertheless exploring relations between mechanical and metabolic EE is valuable, when combined with establishing concurrent validity by comparing mechanical approaches with each other.

2. Methodology

Study population consisted of children with CP (child_CP) and two groups with typical gait: age-related children (child_TG) and adults (adult_TG).

For child_CP, 19 children with spastic diplegic CP (Gross Motor Function Classification Scale I–II), between 5.8 and 12.5 years were tested. Exclusion criteria were walking aids, orthopaedic surgery within two years and Botulinum Toxine treatment within 4 months prior to the test. Five children with CP were excluded because no valid bilateral kinetics could be collected due to pathological or age-related short step length. Three children with CP, for whom measurement of $O_2$-consumption was not available, were included for mechanical approaches only. The study was approved by the local ethical committee.

Typical subjects (18 children, 11 adults) were selected from a previous study [7] when aged -12 years or -20 years and when three trials with valid bilateral kinetics and full visibility for total body kinematics as well as $O_2$-consumption measurement were available (Table 1).

All subjects underwent GA and $O_2$-consumption measurement on the same day in random order. Child_CP walked barefoot, typical subjects performed GA barefoot and measurement of $O_2$-consumption with their normal shoes.
Table 1
Group characteristics for children with cerebral palsy (childe_CP) and the reference groups of children (child_TG) and adults (adult_TG) with typical gait (median (MED) and inter quartile range [IQR1–IQR3]).

<table>
<thead>
<tr>
<th></th>
<th>Child_CP</th>
<th></th>
<th>Child_TG</th>
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<tbody>
<tr>
<td></td>
<td>GA only</td>
<td>GA and O$_2$ measure</td>
<td>(n = 14)</td>
<td>(n = 11)</td>
</tr>
<tr>
<td>Male/female</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age [year]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MED (IQR–IQR3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height [m]</td>
<td>6.5–12.5</td>
<td>6.5–12.5</td>
<td>5.2–11.6</td>
<td>20.9–35.2</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>138.1[130.1–144.1]</td>
<td>139.0[128.9–144.2]</td>
<td>136.8[133.6–145.5]</td>
<td>171.1[168.0–173.3]</td>
</tr>
<tr>
<td>Walking speed [m/s]</td>
<td>29.6[26.3–32.7]</td>
<td>30.1[26.1–33.0]</td>
<td>29.2 [26.5–33.3]</td>
<td>64.5[60.0–68.4]</td>
</tr>
<tr>
<td>GA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O$_2$-measurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>1.12 [1.09–1.21]</td>
<td>1.17 [1.05–1.23]</td>
<td>1.23 [1.17–1.33]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.09[0.88–1.18]</td>
<td>1.19[1.11–1.28]</td>
<td>1.33 [1.27–1.40]</td>
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</table>

Mechanical energy: During GA, total body kinematics and kinetics were collected while walking on a 10-m walkway at self selected comfortable walking speed (\( \text{speed}_{\text{meas}} \)) using an eight-camera VICON System (Mx-camera-workstation, 100 Hz, PlugInGait marker set, VICON, Oxford Metrics, Oxford, UK) and two-embedded force plates (0.4 m x 0.5 m, 1500 Hz, Advanced Mechanical Technology Inc., Watertown, MA) [7].

Mechanical energy was estimated by three different approaches:

1. \( W_{\text{tot}} \) was calculated as the sum of \( W_{\text{ext}} \) and \( W_{\text{int}} \). \( W_{\text{ext}} \) was computed twice, according to Cavagna [Appendix A, Eqs. (1)–(4)] [23], movements of the CoM were estimated by double integration of the ground reaction force (GRF) \( W_{\text{ext}} \) as well as obtained from kinematics \( W_{\text{ext}} \). We were interested in the uselessness of \( W_{\text{int}} \) because in children with gait pathology, it is not always possible to collect valid bilateral GRF. \( W_{\text{ext}} \) was calculated by summing the positive increments in \( E_{\text{kin}} \) changes of the body segments determined by a 12-segment model, based on anthropometric data from Dempster (adults) [24] and Jensen (children) [25]. Translation and rotational energies of the segments were summed [26].

2. \( W_{\text{tot}} \) was calculated without any inter-segmental energy transfer (upper bound; \( W_{\text{tot}} \)). As well as with all possible transfer (lower bound; \( W_{\text{tot}} \)). \( W_{\text{tot}} \) was calculated by determining total energy per segment (\( E_{\text{kin,segment}} \)) and then the sum of \( W_{\text{segment}} \) of all segments, thus allowing no transfer between them (Appendix B, Eq. (1)). \( W_{\text{tot}} \) was calculated by summing all segmental energies \( E_{\text{kin,segment}} \) at each instant of the gait cycle \( E_{\text{kin,segment}} \), thus allowing transfer between segments. \( W_{\text{tot}} \) was equal to the sum of \( E_{\text{kin,segment}} \) at each instant of the gait cycle \( E_{\text{kin,segment}} \).

3. \( W_{\text{tot}} \) was obtained by separate integration of positive and negative joint power profiles \( [J \text{ kg}^{-1} \text{ s}^{-1}] \) for neck, shoulders, elbows, wrists, waist, hips, knees and ankles as obtained from the Vicon Plug-in-Gait model. Positive and negative work performed at each joint was separately summed \( [J \text{ kg}^{-1} \text{ m}] \). The sum of positive and negative joint work of all joints, respectively, gave positive and negative joint work of the whole body \( W_{\text{J}^+} \) and \( W_{\text{J}^-} \). \( W_{\text{tot}} \) was then the sum of \( W_{\text{J}^+} \) and \( W_{\text{J}^-} \).

Metabolic energy: \( \text{O}_2 \)-consumption was measured by breath with K462 (Cosmed, Rome, Italy), by the same experienced investigator using a standardized protocol: 5 min sitting, 3 min standing and 8 min walking at \( \text{speed}_{\text{meas}} \) on a figure eight track (34 m). Testing took place 2–3 h after eating [27]. Average \( \text{O}_2 \)-consumption and respiratory exchange ratio (RER) were calculated at rest and during walking over a 2–3 min steady state period (no visual decrease or increase in \( \text{O}_2 \)-consumption after exclusion of the first three minutes of a period in order to allow subjects to reach steady state). \( \text{speed}_{\text{meas}} \) was calculated as the mean speed during the steady state period of walking. Net \( \text{O}_2 \)-consumption was obtained by subtracting resting \( \text{O}_2 \)-consumption from \( \text{O}_2 \)-consumption during walking and then divided by \( \text{speed}_{\text{meas}} \) to obtain net \( \text{O}_2 \)-cost \( [\text{mL kg}^{-1} \text{ m}^{-1}] \).

To allow comparison with mechanical EE, \( \text{O}_2 \)-cost \( [\text{mL kg}^{-1} \text{ m}^{-1}] \) was converted to joules: \( (4.960 \times \text{RER} + 16.040) \times \text{V}O_2 \) [28].

Statistical analysis was performed SPSS (version 12.0, SPSS Inc.). For each subject, three representative GA trials were analysed. Mechanical energy was normalized for stride length and body weight \( [J \text{ kg}^{-1} \text{ m}^{-1}] \). Furthermore, to investigate variability caused by differences in body dimensions, data were expressed non dimensional [29] [Appendix D]. Validation was investigated over the three groups by comparing mechanical energy approaches with each other and with metabolic EE by a General Linear Model with EE as fixed factor and \( \text{speed}_{\text{meas}} \) as interaction effect (post hoc Bonferroni comparison). Relations between mechanical and metabolic approaches were investigated by Pearson correlation coefficient and interpreted according to Hinkle after performing overall Bonferroni correction (p-values divided by number of comparisons (15)) [30].

For sensitivity analysis child_CP, child_TG and adult_TG were compared with each other by Kruskall–Wallis test, pair-wise post hoc comparison (Mann–Whitney U) and overall Bonferroni correction (18 groups). Variation within groups was evaluated by inter quartile ranges. Significance level was set at \( p < 0.05 \).

3. Results

Variability and interpretation were the same when data were expressed normalized by mass or by net non dimensionalization (Fig. 2A and B). As mass normalization is more intuitive, further results are presented mass normalized.

3.1. Validity

Mechanical and metabolic EE for the total group (mean ± SD) and for the subgroups (median [interquartile range] is presented in Fig. 2. \( \text{W}_{\text{tot}} \) was significantly lower and \( \text{W}_{\text{tot}} \) significantly higher than all other parameters, including net \( \text{O}_2 \)-cost. Also \( W_{\text{J}} \) differed significantly from all other parameters. The only approach that was not different from net \( \text{O}_2 \)-cost was \( \text{W}_{\text{tot}} \).

Correlation analysis revealed moderate correlations for \( W_{\text{J}} \) and \( \text{W}_{\text{tot}} \) with net \( \text{O}_2 \)-cost \((r = 0.51–0.52, p < 0.001)\). No correlation was found between the other mechanical energy approaches and net \( \text{O}_2 \)-cost \((r = 0.02–0.29, p > 0.05)\) (Fig. 3). Few correlations were found between different mechanical energy approaches. Apart from high relations within an approach \((W_{\text{J}} r = 0.82; W_{\text{tot}} r = 0.80, p < 0.001)\), only a relation between \( W_{\text{J}} \) and \( \text{W}_{\text{tot}} \) \((r = 0.47, p = 0.015)\) was observed.

3.2. Sensitivity

Comparison between typical and pathological gait is summarized in Table 2. \( \text{W}_{\text{tot}} \) \( W_{\text{J}} \) and net \( \text{O}_2 \)-cost discriminate best between pathological and typical gait.

Within-group variation for \( \text{W}_{\text{tot}} \)-F and \( \text{W}_{\text{tot}} \)-K was low in all three groups (resp. 17–23% and 25–26%). Variation in \( \text{W}_{\text{tot}} \) was higher in adult_TG (37%) than in child_TG (20%) and child_CP (30%). Variation in \( \text{W}_{\text{tot}} \) was highest in adult_TG (47%) and lower in child_TG (20%) and child_CP (17%). \( W_{\text{J}} \) showed low variation in typical gait (adult_TG: 25%; child_TG 18%) and high variation 44% in child_CP. O$_2$-cost showed low variation in adults (17%) and high variation in child_TG (48%) and child_CP (32%).
Fig. 2. Median (MED) and interquartile range [IQ1–IQ3] for subgroups as well as mean and standard deviation (SD) for the total group of the different mechanical approaches and net O₂-cost. A: Graphical representation of mass normalized mean for the total group (bars) and median and IQ1 and IQ3 for the three groups separately: children with cerebral palsy (child_CP: diamonds, n = 11), children (child_TG: squares) and adults (adult_TG: triangles) with typical gait. B: Graphical representation of net non dimensional mean for the total group (bars) and median and IQ1 and IQ3 for the three groups separately: children with cerebral palsy (child_CP: diamonds, n = 11), children (child_TG: squares) and adults (adult_TG: triangles) with typical gait. C: Numerical representation for the total group, as well as for child_CP, child_TG and adult_TG separately. Letters a-f indicate significant differences between the energy parameters (p < 0.05).

Table 2
p-values for comparison between typical and pathological gait as well as between adult and pediatric gait with non parametric Kruskall–Wallis test and Mann–Whitney U post hoc comparison and overall Bonferroni correction (18 comparisons).

<table>
<thead>
<tr>
<th></th>
<th>Kruskall–Wallis</th>
<th>Mann–Whitney U</th>
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<tbody>
<tr>
<td></td>
<td>Post hoc comparison: Mann–Whitney U</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pathologic – typical gait</td>
<td>Adult – pediatric gait</td>
</tr>
<tr>
<td></td>
<td>Child CP–child_TD</td>
<td>Child CP–adult_TD</td>
</tr>
<tr>
<td>W_{tot,F}</td>
<td>&lt;0.001*</td>
<td>0.018</td>
</tr>
<tr>
<td>W_{tot,k}</td>
<td>&lt;0.001*</td>
<td>1.0</td>
</tr>
<tr>
<td>W_{tot,LB}</td>
<td>0.001*</td>
<td>1.0</td>
</tr>
<tr>
<td>W_{tot,UB}</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>W_{j}</td>
<td>&lt;0.001*</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Net O₂-cost</td>
<td>&lt;0.001*</td>
<td>0.036</td>
</tr>
</tbody>
</table>

* Significant differences at p < 0.05.
4. Discussion

This study aimed at evaluating clinical usefulness of mechanical energy estimation in children with CP. Three different mechanical energy approaches were validated against $O_2$-cost and each other, and sensitivity was established. $W_I$ and $W_{SSE, LB}$ were the most promising approaches for clinical use; $W_{tot}$ underestimated EE and was not sensitive enough to discriminate pathology; $W_{SSE, UB}$ overestimated total EE.

Mechanical energy was higher than reported in the literature, probably because head, arms and trunk were included separately where most other studies include head, arms and trunk as one segment [31,32] or not at all [33], thus underestimating total EE. Due to different assumptions, the three approaches were expected to quantify EE differently. $W_{tot}$ was expected to be lowest since it only takes into account positive work, where both $W_{SSE}$ and $W_I$ also take into account negative done by the muscles. On the other hand, $W_{SSE, UB}$ was expected to be highest, since it does not take into account any transfer between adjacent segments that leads to more efficient gait. This was confirmed with $W_{tot}$ being significantly lower than all other approaches, implicating that $W_{tot}$ underestimates EE. $W_{SSE, UB}$ was higher than all other mechanical parameters as well as $O_2$-cost, indicating that $W_{SSE, UB}$ overestimates EE and indeed at least some form of transfer is present. $W_{tot}$ did not correlate with $O_2$-cost either, suggesting that it does not include enough information (such as negative work) to be a realistic view of total EE. $W_I$ and $W_{SSE}$ showed low to moderate relations with $O_2$-cost. Higher relations were not expected since mechanical approaches cannot account for all sources of EE. Furthermore the relation between metabolic and mechanical EE might be biased by limited reproducibility, as well as by high variability of metabolic EE. As this high variability might be caused by experimental errors, we investigated influence of normalization [29], conversion technique (ml to J) as well as influence of differences in speed$_{conf}$ between GA and metabolic measurements. Neither normalization, nor conversion technique influenced variability and differences in speed$_{conf}$ between both measurements were small and not significant.

In previous literature no clear relation between metabolic and mechanical EE has been observed [12,18,20], probably because it is difficult to find a relation within a small range of EE in a single population. By evaluating EE over three groups together, we created a broad range from efficient adult to inefficient pathological gait. $W_I$ and $W_{SSE}$ correlating moderately over this broad range, despite above mentioned factors that might obscure their relation, indicates that, however only partly, these approaches capture changes in EE that are also captured by $O_2$-cost. As mechanical approaches can only capture EE partly, the methods cannot substitute each other.

For clinical use, a parameter should also be sensitive enough to discriminate between pathological and typical gait, as investigated by evaluating differences between groups. $W_{tot}$ and $W_{SSE, LB}$ were least sensitive. They showed small and clinical irrelevant differences or could not discriminate between groups at all. Van den Hecke et al. reported higher differences in $W_{tot}$ between children with hemiplegic and typical gait [16]. They did however not report on statistical significance. $W_{SSE, UB}$ was sensitive enough to discriminate between all three groups, which is in agreement with McDowell et al. [20]. $W_I$ was higher in child_CP, compared to adult_TG and child_TG, who did not differ from each other. This is in agreement with Van de Walle et al., where $W_I$ did not differ from adult values after the age of 9 years and both $W_{SSE}$ and net $O_2$-cost showed a decrease by increasing age until adult ages [7]. $O_2$-cost was sensitive enough to discriminate between pathology as well as development. Caty et al. also found $O_2$-cost to be more sensitive to changes after treatment than $W_{tot}$ [22].

For good sensitivity a parameter should also show low variation in typical adult gait, as was found in $W_I$ and $O_2$-cost but not in $W_{SSE, UB}$. This study confirms again high variability in $O_2$-cost in pediatric typical gait that was previously reported [7,8,34]. Possible explanations are variability in resting oxygen consumption, variability in efficiency of muscular contraction as well as variability in age-related changes in physical development that affect metabolic, more than mechanical EE. Normalization techniques [29] of $O_2$-cost and speed$_{conf}$ did not influence this difference in variability and were therefore not reported. High
variability in O2-cost complicates its clinical interpretation, as an observed increase can be either pathology- or age-related. Mechanical approaches might therefore be a useful supplement to gain better insight into causes of increased EE. When considering validity and sensitivity, \( W_i \) seems the best choice for evaluating mechanical EE in children with CP. A disadvantage of \( W_i \) is that external force measurements of both feet separately are needed in one trial. This collection of valid kinetics in pathologic gait is often difficult. From 19 patients that were tested, 5 patients had to be excluded for this reason. Although an approach without kinetics would be appreciated in clinical practice, current results confirm that one should be careful with kinematic data in calculating work. Collection of bilateral kinetics, however, needs at least three force plates in a row. When measuring GRF of both legs over one gait cycle with only two force plates, GRF of the contra-lateral leg is not available during first phase of double support. This missing part will then have to be completed with GRF data of the beginning of the next gait cycle, as was done in this study. This however assumes symmetry between subsequent cycles, which might not always be valid in children, let alone children with CP. This is a limitation of this study, however, all GRF profiles were inspected visually and excluded when asymmetries were found.

In conclusion mechanical EE approaches seem to be a valuable supplement to metabolic EE. Although frequently used, metabolic EE clearly has disadvantages in clinical decision making in children. \( W_i \) is the preferred mechanical approach for clinical use in children with diplegia, whenever collection of bilateral kinetics is feasible. \( W_{\text{tot}} \) might also be a valuable, but one has to be aware of the higher variability. Furthermore mechanical energy approaches should not replace, but supplement metabolic energy estimation, since results confirm again that not all EE is captured in mechanical approaches.

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Conflic of interest statement

There are no financial and personal relationships of any of the authors listed below with other people or organisations that could appropriately influence (bias) this work.

Appendix A. Positive external work according to Cavagna [23]

\[
E_{\text{pot}} = M_{\text{tot}} \times 9.81 \times \text{CoM}(Z) \quad [\text{J}]
\]

(1)

\[
E_{\text{kin}} = \frac{1}{2} \times M_{\text{tot}} \times \left( v_x^2 + v_y^2 + v_z^2 \right) \quad [\text{J}]
\]

(2)

\[
E_{\text{tot}} = E_{\text{pot}} + E_{\text{kin}} \quad [\text{J}]
\]

(3)

\[
W_{\text{tot}} = \sum_{i=1}^{J} \Delta E_{\text{tot}} \quad [\text{J}]
\]

(4)

\( GC \) is the number of instants during the gait cycle.

Appendix B. Analysis of the energy changes of moving body segments (sum of segmental energies)

\[
W_{\text{SSE-LB}} = \sum_{i=1}^{N} \left\{ \sum_{j=1}^{GC} \Delta E_{\text{segment}} \right\} \quad [\text{J}]
\]

(1’)

\[
E_{\text{segment}} = E_{\text{pot}} + E_{\text{kin}}
\]

\( N \) is the number of segments, in this case 12 (cfr. model \( W_{\text{tot}} \)).

\[
W_{\text{SSE-LB}} = \sum_{j=1}^{GC} \Delta E_{\text{tot}} \quad [\text{J}]
\]

(2’)

\( GC \) is the number of instants during the gait cycle.

\[
E_{\text{tot}} = \sum_{i=1}^{J} \sum_{j=1}^{GC} \Delta E_{\text{segment}} \quad [\text{J}]
\]

(3)

\( N \) is the number of segments, in this case 12.

Appendix C. Work calculated by integration of joint powers

\[
W_j = \sum_{i=1}^{J} \sum_{j=1}^{GC} \Delta P_{\text{joint}} \cdot \Delta t, \text{ if } P_{\text{joint}} > 0 \quad [\text{J}]
\]

(1)

\[
W_j = \sum_{i=1}^{J} \sum_{j=1}^{GC} \Delta P_{\text{joint}} \cdot \Delta t, \text{ if } P_{\text{joint}} < 0 \quad [\text{J}]
\]

(2)

\( GC \) is the number of instants during the gait cycle. \( N \) is the number of segments, in this case 14.

\[
W_j = W_j^+ + \left| W_j^- \right| \quad [\text{J}]
\]

(3)

Appendix D. Net non dimensionalization according to Schwartz [29]

\[
\text{speed}_{\text{nn}} = v \times \left( \frac{1}{\sqrt{V_{\text{Leg}}}} \right)
\]

Oxygen consumption_{nn} = \left( O_2 \text{ gross} - O_2 \text{ rest} \right) \times \left( \frac{1}{\text{mg} \sqrt{V_{\text{Leg}}}} \right)

Oxygen cost_{nn} = \left( O_2 \text{ gross} - O_2 \text{ rest} \right) \times \left( \frac{1}{\text{mg}} \right)

References