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Analysis of mechanical energy in thigh, calf and foot during gait in children with cerebral palsy

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A R T I C L E I N F O

Keywords:
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Lower limbs
Recovery coefficient

A B S T R A C T

Background: Many studies on children with cerebral palsy (CP) have focused on metabolic energy, however research on the mechanical energy in the lower limbs is sparse.

Research question: What differences of mechanical energies in the lower limbs exist between the children with CP and typically developing (TD) children during gait? The purpose of this research was to analyse the mechanical energy changes of the lower limbs of children with CP during walking and compare them with TD children.

Methods: Twelve children with CP including 8 diplegic and 4 hemiplegic without severity levels (aged 4–22 year old) and 14 TD participants (aged 5–15 year old) walked barefoot in a gait lab where a motion capture system collected marker data during walking. The translational and rotative kinetic energy and potential energy in the thigh, calf and foot were then calculated using the marker data. Gait parameters, e.g., stride frequency, pace, stride length, stride width, were also obtained.

Findings: The results show that the children with CP had significantly lower values than the TD group in terms of kinetic energy and potential energy. This was especially seen in the thigh where the energy recovery coefficient in the children with CP was 31% compared with 43% in the TD group. In the calf and foot, the CP and TD groups had similar energy recovery to the TD group, i.e. not significantly different clinically. The gait parameters showed that children with CP had slower walking speed, shorter stride length, larger step width than TD but similar cadence to TD.

Interpretation: The energy recovery coefficient represents the efficiency of exchanges of kinetic and potential energies. The higher its value, the better the energy use during gait.

Significance: This study concluded that CP gait is weaker in the use of energy than TD gait. To our best knowledge, this study is the first one to analyse mechanical energy changes in the lower limbs for CP and TD groups during gait.

1. Introduction

Cerebral Palsy (CP) is a permanent non-progressive movement disorder syndrome that can be partially relieved by early intervention. This condition is usually secondary to abnormal brain development in the developing foetus or infant [1]. Sadowska et al. [13] divided CP into several forms according to the type of movement disorder and the clinical presentation. Jessica et al. [2] investigated maximum energy consumption during walking in children with CP and found that the energy consumption of the CP group was 1 to 2 times that of the TD group. Johnston et al. [3] compared the energy expenditure of walking in children with CP at different levels of the Gross Motor Function Classification System (GMFCS) with TD children. The gas dilution method was used to assess energy expenditure and found that children with CP had higher energy expenditure during walking than TD children. Abram et al. [14] found that people prefer to walk in the most energy-efficient way. Pouliot-Laforte [4] studied the relationship between the walking ability of children with bilateral spastic CP and the muscle strength of their lower limbs and calculated the Pearson coefficient and regression model of the two. In terms of mechanical energy and recovery efficiency, Bennett et al. [21] found that children with CP had a 33% smaller energy recovery factor than TD children by using inter-group measures to analyse the differences between children with CP and the control group. Though Olney et al. [22] investigated

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Table 1
Demography information and clinical condition for the participants.

Group		Mean	Std. deviation	Minimum	Maximum	p
Age (year old)	TD	12.1	2.5	9	15	0.173
	CP	10.0	5.1	4	22	
Bodymass (kg)	TD	46.3	14.0	26.0	66.4	0.077
	CP	34.8	17.8	14.2	64.0	
Height (mm)	TD	1554.7	160.3	1290	1768	0.019*
	CP	1357.5	238.7	1026	1718	
InterAsisDistance (mm)	TD	211.8	26.4	174	265	0.014*
	CP	180.5	33.8	120	228	
MeanLegLength (mm)	TD	804.3	90.6	652.5	942.5	0.025*
	CP	685.5	158.2	433.5	902.5	
LegLength (mm) Left	TD	807.7	93.6	655	945	0.023*
	CP	685.4	160.1	435	900	
KneeWidth (mm) Left	TD	90.9	8.9	77	103	0.004*
	CP	78.4	11.0	61	96	
AnkelWidth (mm) Left	TD	73.0	10.2	59	100	<0.0001*
	CP	55.1	9.7	39	69	
LegLength (mm) Right	TD	800.8	88.4	650	940	0.027*
	CP	685.6	156.5	432	905	
KneeWidth (mm) Right	TD	91.2	8.5	78	105	0.003*
	CP	79.3	9.8	62	97	
AnkelWidth (mm) Right	TD	72.6	9.0	58	93	<0.0001
	CP	55.8	8.2	44	70	

Note: CP $n = 12$, TD $n = 14$. CP group: 4 females and 8 males, TD group: all males. CP types: diplegic 8, hemiplegic 4. Data collected between 2015 and 2022.

mechanical energy patterns for children with CP during gait [22], Russell et al. [23] studied CP related gait [23], and Nardon et al. [24] reviewed many studies on energetics of walking in individuals with CP and TD [24], there has been little research directly on the energies of the thigh, calf and foot during gait in children with CP compared with TD. Previous studies also reported that unimpaired people walk like a pendulum to make energy exchange between kinetic and potential forms [25, 5], i.e. that two energies occur out of phase (one up and another down) and thus exchange each other to save total energy during movement, but the question of whether the thigh, calf and foot move like a pendulum has not been investigated. Further, the pendulum model of mechanical energy transfer in gait and its application to children with CP is limited.

Currently, gait analysis is carried out using passive reflective markers through 3D stereophotogrammetry [15–17]. Motion capture system has been used to collect walking parameters, including step length, walking speed, gait cadence etc. However, there is little research on the mechanical energy of the lower limbs during walking in children with CP. So far, no studies have been done on the mechanical energy parameters, e.g., translational and rotative kinetic energy, potential energy, and energy recovery coefficient, for the thigh, calf and foot during gait for children with CP and TD children. These energy parameters and their coordinative way during gait may provide a new indication on the assessment of gait, especially for patient gait. Therefore, this current study intended to fill the research gap. The research hypotheses were that 1) the segments of lower limbs, i.e. thigh, calf and foot, may work like a pendulum to save energy expenditure during gait, and 2) children with CP may have weaker efficiency in energy use than TD children. The purpose of this study was two-fold: first to investigate the mechanical energy changes of lower limbs during walking in children with CP, and second to compare these results with the TD children group.

2. Methods and materials

All existing data were originally collected (2015–2022) at the Motion & Gait Analysis Laboratory at the Centre, where there is an ethical approval in the hospital and all participants had signed written consent forms when attended to the gait labs. As the data of this study were selected from the existing database without contacting participants, the school ethical committee granted a waiver of an extra ethical application for this current study.

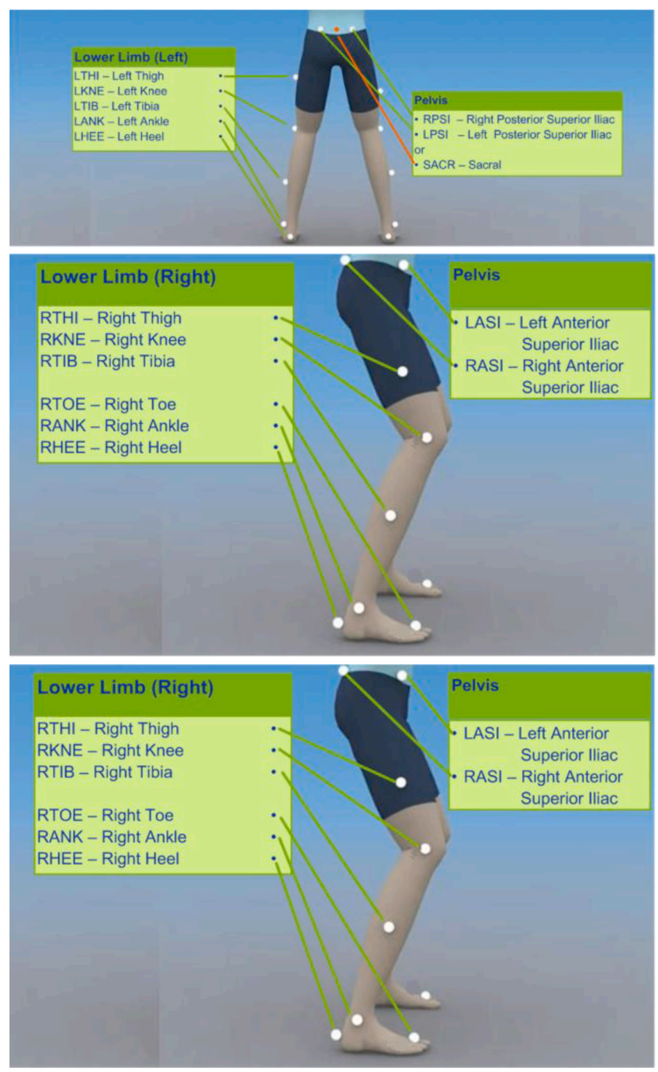


Fig. 1. Vicon marker set used in this study.

2.1. Subject data

The gait data of children with CP and TD were extracted from the database. Firstly, data of 69 participants, including 37 children with CP and 32 TD children were randomly selected from the database in the Clinical Gait Lab. Some of the participants were excluded if they were missing a clean forceplate strike or if their markers were lost during the trial. After screening, 12 children with CP and 14 TD subjects were selected for analysis. All subjects were able to walk barefoot independently. Anthropometric measurements including weight, height, segment length, knee joint width, ankle joint width, and age range were obtained from the database as shown in Table 1. Finally, 74 and 69 trials for CP and TD, respectively, were used in analysis.

2.2. Laboratory equipment

The laboratory has an 18 m-long walkway and is 9 m wide. A Vicon® motion capture system, including 12 highly specialized 3D cameras, 4 synchronized HD video cameras with 4 force plates embedded flush with the lab floor, were used when initially collecting the gait data.

2.3. Data collection

During data collection, each subject was asked to stand still in the motion capture area after retro-reflective markers had been positioned on subjects. The exact location of the attached markers was selected according to bony anatomical landmarks on both sides of the body, which included the anterior superior iliac spine, the posterior superior iliac spine, the lower third of the lateral thigh, the external epicondylar of the femur, the internal epicondylar of the femur, the lower third of the lateral leg, the medial malleolus, the lateral malleolus, and the calcaneal portion lying on the same level as the medial and lateral malleolus as Fig. 1. After the static test, subjects were asked to walk as they would naturally do in every-day life. To capture an entire good gait cycle on the force plates and increase the probability of effective walking, most subjects were required to repeat many trials.

2.4. Energy calculation

Mechanical energy is divided into kinetic energy and potential energy. The former is related to the mass and velocity of an object, and the latter is related to the mass of the object and its position within the corresponding reference frame. Regarding calculation, the following formulas were used:

$$KE = \frac{1}{2}mv^2 \quad (1)$$

where *KE* is translational kinetic energy, *m* is the mass of the body segment and *v* is the velocity of the centre of mass (CoM). From the marker data, the joint centres were estimated using Vicon® Plug-in-Gait model. The mass and CoM for each segment or whole lower limb were calculated by referring to the relative mass of the whole body and the relative length of the segment [11,12].

$$PE = mgh \quad (2)$$

where *PE* is potential energy, h is the height of CoM relative to a base level, e.g., the ground, and *g* is the gravitational constant, approximately 9.81 m/s^2.

Rotational kinetic energy was calculated using the equation:

$$RKE = \frac{1}{2}I_c\omega^2 \quad (3)$$

Where I_c is the moment of inertia of the segment about its CoM, with units of kgm^2, and ω is the angular velocity of the segment, (rad/s). ω was calculated by using a vector from the proximal and distal joints in 3D space during walking. I_c was calculated by referring to the radius of gyration to segment length as the references [11,12].

To analyse how much the kinetic and potential energies exchange, an energy recovery coefficient was used as below:

$$Recovery_n = \frac{(\Delta PE + \Delta KE) - \Delta(PE + KE)}{(\Delta PE + \Delta KE)} \quad (4)$$

Where ΔPE is the maximum change in the potential energy, ΔKE is the maximum change in the kinetic energy and Δ(PE + KE) is the maximum change in the sum of the two energies [5]. The energy recovery coefficient is a dimensionless coefficient, meaning that the higher, the better.

All energies were calculated during a gait cycle which was the centre of data capture volume and where walking speed was stable. The cycle was defined manually from one foot strike to the next foot strike for each trial. Finally, 38 and 35 gait trials for children with CP and TD groups were analysed.

Table 2
Comparison of gait parameters between the CP and TD groups.

Dependant variable		Mean	Std. error	95% confidence interval		Sig.[d]
				Lower bound	Upper bound	
RightCadence (step/min)	CP	120.098[a]	2.84	114.38	125.81	0.340
	TD	116.125[a]	2.99	110.11	122.14	
RightWalkingSpeed (m/s)	CP	0.784[a]	0.03	0.73	0.84	
	TD	1.329[a]	0.03	1.27	1.39	
RightFootOff (%)	CP	60.747[a]	0.52	59.71	61.79	
	TD	57.288[a]	0.55	56.19	58.39	
RightStrideLength (m)	CP	0.780[a]	0.01	0.75	0.81	
	TD	1.382[a]	0.02	1.35	1.41	
RightStepLength (m)	CP	0.402[a]	0.01	0.38	0.42	
	TD	0.696[a]	0.01	0.68	0.72	
RightStepWidth	CP	0.159[a]	0.01	0.15	0.17	
	TD	0.123[a]	0.01	0.11	0.13	
LeftCadence (step/min)	CP	119.901[a]	2.81	114.24	125.56	0.158
	TD	114.035[a]	2.96	108.07	120.00	
LeftWalkingSpeed (m/s)	CP	0.775[a]	0.02	0.73	0.82	
	TD	1.312[a]	0.03	1.26	1.36	
LeftFootOff (%)	CP	59.731[a]	0.53	58.67	60.79	
	TD	56.952[a]	0.55	55.83	58.07	
LeftStrideLength (m)	CP	0.773[a]	0.02	0.74	0.80	
	TD	1.392[a]	0.02	1.36	1.42	
LeftStepLength (m)	CP	0.375[a]	0.01	0.36	0.39	
	TD	0.695[a]	0.01	0.68	0.71	
LeftStepWidth	CP	0.148[a]	0.01	0.14	0.16	
	TD	0.114[a]	0.01	0.10	0.13	
norRWalkingSpeed (1/s)	CP	0.585[a]	0.02	0.54	0.63	
	TD	0.858[a]	0.02	0.81	0.90	
norRStrideLength	CP	0.567[a]	0.01	0.55	0.59	
	TD	0.887[a]	0.01	0.86	0.91	
norRStepLength	CP	0.290[a]	0.01	0.28	0.30	
	TD	0.447[a]	0.01	0.43	0.46	
norLWalkingSpeed (1/s)	CP	0.575[a]	0.02	0.54	0.61	
	TD	0.848[a]	0.02	0.81	0.89	
norLStrideLength	CP	0.560[a]	0.01	0.54	0.58	
	TD	0.893[a]	0.01	0.87	0.92	
norLStepLength	CP	0.274[a]	0.01	0.26	0.28	
	TD	0.446[a]	0.01	0.43	0.46	

Note: all pairs $p < 0.001$ except Cadence. norX: normalised with height. Footoff % is stance phase% of a gait cycle.

[a] . Based on modified population marginal mean.

Table 3
Kinetic and potential energy (Joule) parameters of the segments and whole lower limb.

Part			Mean	Std. error	95% Confidence interval		Sig.[b]
					Lower bound	Upper Bound	
thigh	maxKE	CP	3.370[a]	0.21	2.95	3.79	
		TD	7.754[a]	0.24	7.28	8.22	
	minKE	CP	0.509[a]	0.04	0.43	0.59	
		TD	1.156[a]	0.04	1.07	1.24	
	RangeKE	CP	2.861[a]	0.19	2.49	3.23	
		TD	6.598[a]	0.21	6.19	7.01	
	maxPE	CP	25.868[a]	0.19	25.49	26.25	
		TD	27.373[a]	0.22	26.94	27.80	
	minPE	CP	23.809[a]	0.18	23.46	24.16	
		TD	24.786[a]	0.20	24.39	25.18	
	RangePE	CP	2.059[a]	0.10	1.87	2.25	
		TD	2.587[a]	0.11	2.37	2.80	
foot	maxKE	CP	3.340[a]	0.17	3.00	3.68	
		TD	5.747[a]	0.20	5.36	6.13	
	minKE	CP	0.000[a]	0.00	0.00	0.00	0.188
		TD	0.000[a]	0.00	0.00	0.00	
	RangeKE	CP	3.340[a]	0.17	3.00	3.68	
		TD	5.747[a]	0.20	5.36	6.13	
	maxPE	CP	1.003[a]	0.02	0.96	1.05	
		TD	1.244[a]	0.03	1.19	1.29	
	minPE	CP	0.360[a]	0.01	0.33	0.39	
		TD	0.455[a]	0.02	0.42	0.49	
	RangePE	CP	0.643[a]	0.02	0.61	0.67	
		TD	0.789[a]	0.02	0.75	0.82	
calf	maxKE	CP	3.396[a]	0.18	3.03	3.76	
		TD	6.106[a]	0.21	5.70	6.51	
	minKE	CP	0.019[a]	0.00	0.01	0.02	
		TD	0.029[a]	0.00	0.02	0.03	
	RangeKE	CP	3.378[a]	0.18	3.02	3.74	
		TD	6.076[a]	0.21	5.67	6.48	
	maxPE	CP	5.346[a]	0.07	5.20	5.49	
		TD	5.803[a]	0.08	5.64	5.96	
	minPE	CP	4.328[a]	0.06	4.22	4.44	
		TD	4.689[a]	0.06	4.57	4.81	
	RangePE	CP	1.018[a]	0.03	0.95	1.09	0.067
		TD	1.113[a]	0.04	1.04	1.19	
	maxKE	CP	7.857[a]	0.46	6.95	8.76	
		TD	15.787[a]	0.51	14.77	16.80	
	minKE	CP	0.399[a]	0.03	0.33	0.46	
		TD	0.901[a]	0.04	0.83	0.97	
	RangeKE	CP	7.458[a]	0.44	6.59	8.33	
		TD	14.886[a]	0.49	13.91	15.86	
	maxPE	CP	31.884[a]	0.29	31.32	32.45	
		TD	33.886[a]	0.32	33.25	34.52	
	minPE	CP	28.734[a]	0.24	28.26	29.21	
		TD	30.413[a]	0.27	29.88	30.95	
Whole Lower limb	RangePE	CP	3.150[a]	0.12	2.92	3.38	0.069
		TD	3.473[a]	0.13	3.21	3.73	

Note: almost all $p < 0.001$ except a couple of variables. Whole lower limb includes thigh, calf and foot together. Data include both sides combined.
[a] Covariates appearing in the model are evaluated at the following values: height = 1.4509, Bodymass = 40.290.

Table 4
Normalised energy parameters for segments and whole lower limbs.

Part			Mean	Std. error	95% Confidence interval		Sig.[b]
					Lower bound	Upper bound	
thigh	NORmaxKE	CP	0.07	0.00	0.06	0.08	
		TD	0.13	0.00	0.12	0.14	
	NORminKE	CP	0.01	0.00	0.01	0.01	
		TD	0.02	0.00	0.02	0.02	
	NORRangeKE	CP	0.06	0.00	0.05	0.07	
		TD	0.11	0.00	0.11	0.12	
	NORmaxPE	CP	0.44	0.00	0.44	0.45	
		TD	0.47	0.00	0.46	0.47	
	NORminPE	CP	0.41	0.00	0.40	0.41	
		TD	0.42	0.00	0.42	0.43	
	NORRangePE	CP	0.04	0.00	0.03	0.04	
		TD	0.04	0.00	0.04	0.05	
foot	NORmaxKE	CP	0.06	0.00	0.05	0.06	
		TD	0.10	0.00	0.09	0.11	
	NORminKE	CP	0.00	0.00	0.00	0.00	0.753
		TD	0.00	0.00	0.00	0.00	
	NORRangeKE	CP	0.06	0.00	0.05	0.06	
		TD	0.10	0.00	0.09	0.11	
	NORmaxPE	CP	0.02	0.00	0.02	0.02	
		TD	0.02	0.00	0.02	0.02	
	NORminPE	CP	0.01	0.00	0.01	0.01	
		TD	0.01	0.00	0.01	0.01	
	NORRangePE	CP	0.01	0.00	0.01	0.01	
		TD	0.01	0.00	0.01	0.01	
calf	NORmaxKE	CP	0.06	0.00	0.06	0.07	
		TD	0.11	0.00	0.10	0.11	
	NORminKE	CP	0.00	0.00	0.00	0.00	
		TD	0.00	0.00	0.00	0.00	
	NORRangeKE	CP	0.06	0.00	0.06	0.07	
		TD	0.11	0.00	0.10	0.11	
	NORmaxPE	CP	0.09	0.00	0.09	0.09	
		TD	0.10	0.00	0.10	0.10	
	NORminPE	CP	0.07	0.00	0.07	0.08	
		TD	0.08	0.00	0.08	0.08	
	NORRangePE	CP	0.02	0.00	0.02	0.02	0.247
		TD	0.02	0.00	0.02	0.02	
	NORmaxKE	CP	0.15	0.01	0.13	0.17	
		TD	0.27	0.01	0.25	0.29	
	NORminKE	CP	0.01	0.00	0.01	0.01	
		TD	0.02	0.00	0.01	0.02	
	NORRangeKE	CP	0.14	0.01	0.13	0.16	
		TD	0.26	0.01	0.24	0.27	
	NORmaxPE	CP	0.55	0.00	0.54	0.56	
		TD	0.58	0.00	0.57	0.59	
	NORminPE	CP	0.49	0.00	0.48	0.50	
		TD	0.52	0.00	0.51	0.53	
Whole lower limbs	NORRangePE	CP	0.06	0.00	0.05	0.06	0.390
		TD	0.06	0.00	0.05	0.06	

Note: all $p < 0.0001$ when p is not given. NORX means the variables normalised by height and body mass.

2.5. Statistical analysis

SPSS v 25 was used for statistical analysis of the data. Multivariate in General Linear Model was used to compare the variables of the two groups. The compared parameters were put into dependant Variables, and then the Group (i.e., CP/TD) was put in Fixed Factor. Considering that height and weight may have an impact on the results, while taking Group as the main effect, height and weight were used as covariates in interaction, so that the results obtained considered the effects of height, weight, and differences between groups. Adjustment for multiple comparisons: Bonferroni. In addition, some energy variables were normalised by height and body mass. When the normalised variables were compared, there was no covariates used. The significance level was set at $p \leq 0.05$.

Power analysis: As this study is brand new and no previous studies were refereed, a posteriori power analysis has been done. Given the conditions that the energy recovery coefficient is a major variable, power as 80% and $\alpha = 0.05$, the clinical difference is assumed as 10% and standard errors were roughly 1.35% from the results (Table 4), the sample size required should be roughly 12 [26]. Therefore, the sample size used was reasonably fine in terms of statistical power.

3. Results

3.1. Demography and gait parameters

The demographic detail is shown in Table 1.
The gait parameters are reported in Table 2.

Table 5
The energy recovery coefficients (%) for three segments and whole lower limb.

Part		Mean	Std. error	95% Confidence Interval Lower bound	Upper bound	Sig.[b]
thigh	CP	31.631[a]	1.16	29.34	33.92	<0.0001
	TD	43.105[a]	1.30	40.54	45.67	
foot	CP	6.656[a]	0.28	6.10	7.21	0.113
	TD	7.325[a]	0.31	6.71	7.94	
calf	CP	6.435[a]	0.48	5.48	7.39	0.015
	TD	4.650[a]	0.54	3.58	5.72	
Whole lower limb	CP	12.124[a]	0.66	10.82	13.43	0.001
	TD	15.375[a]	0.74	13.91	16.84	

[a] . Covariates appearing in the model are evaluated at the following values: height = 1.4509, Bodymass = 40.290.

3.2. Kinetic energy parameters

The results are shown in Tables 3, 4. When comparing the lower limbs, the normalised maximum kinetic energy of the TD group was roughly 44% higher than the CP group. When the lower limbs were divided into three segments for comparison, the TD group was still significantly higher than the CP group. The maximum kinetic energy of the TD was roughly 47% higher than CP groups in the thigh. Moreover, the changes of kinetic energy (range) were higher in TD than CP. In physics, the energy change is roughly equal to work exported by an object, and thus CP had less work done than TD in gait as in Tables 3,4.

3.3. Potential energy parameters

When compared as a whole lower limb, the normalised maximum potential energy of the TD group was roughly 5.2% higher than the CP group. When comparing the segments separately, the normalised maximum potential energy of the TD group in the tight was 6.4% higher than that of the CP group. However, the changes of normalised potential energy (range) were not significant higher in TD than children with CP as in Table 4.

3.4. Recovery coefficient of lower limbs

When the lower limbs were analysed as a whole, the energy recovery coefficient of the TD group was 3.2% higher than that of the CP group ($p < 0.001$). However, when the lower limbs were investigated separately,

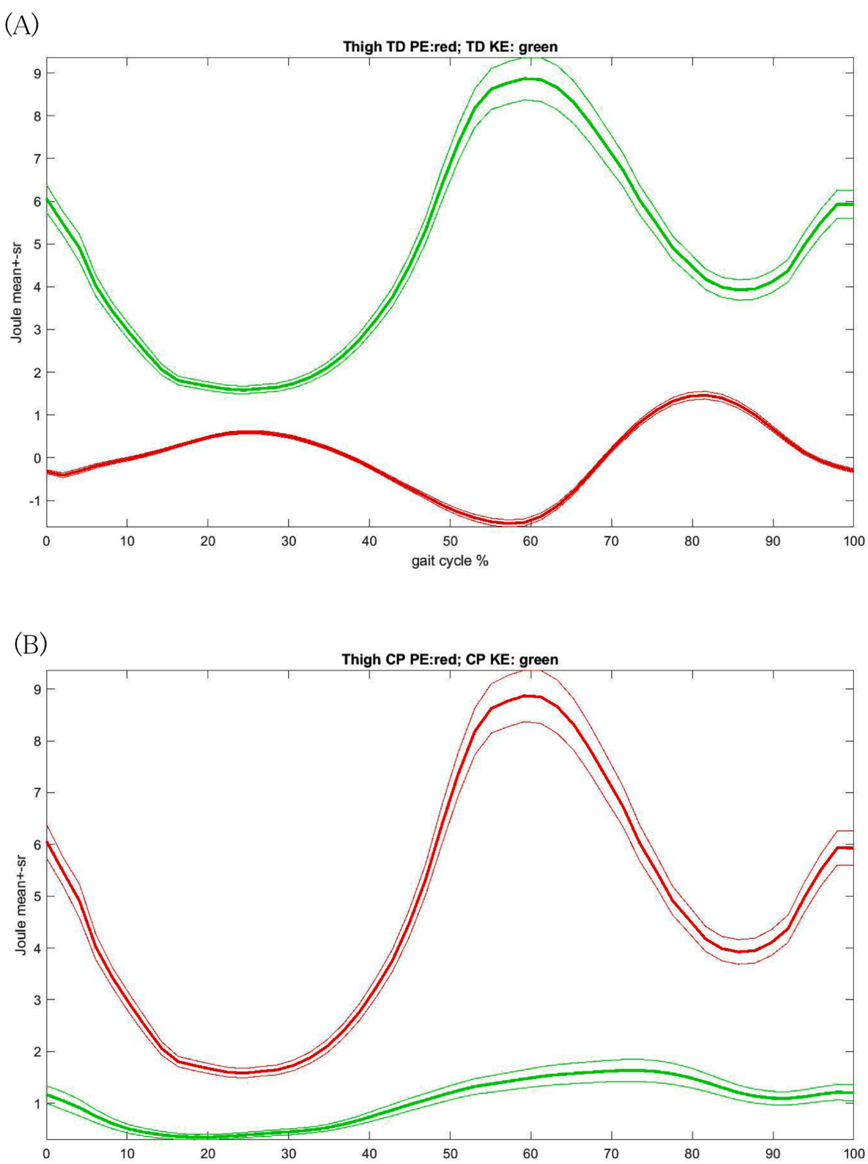


Fig. 2. The energy changes of the thigh during gait in TD and CP groups. Note: Thick lines are means and thin lines standard errors. Rotative energy is neglected due to being too small compared with PE and KE. Using left and right sides together, the number of trials was 74 and 69 for CP and TD groups, respectively. When plotting potential energy, each trial has been shifted to the mean position as reference level. The kinetic and potential energy fluctuations were strongly out of phase (one up while another down) in TD group as (A) but were not strongly in CP group as (B).

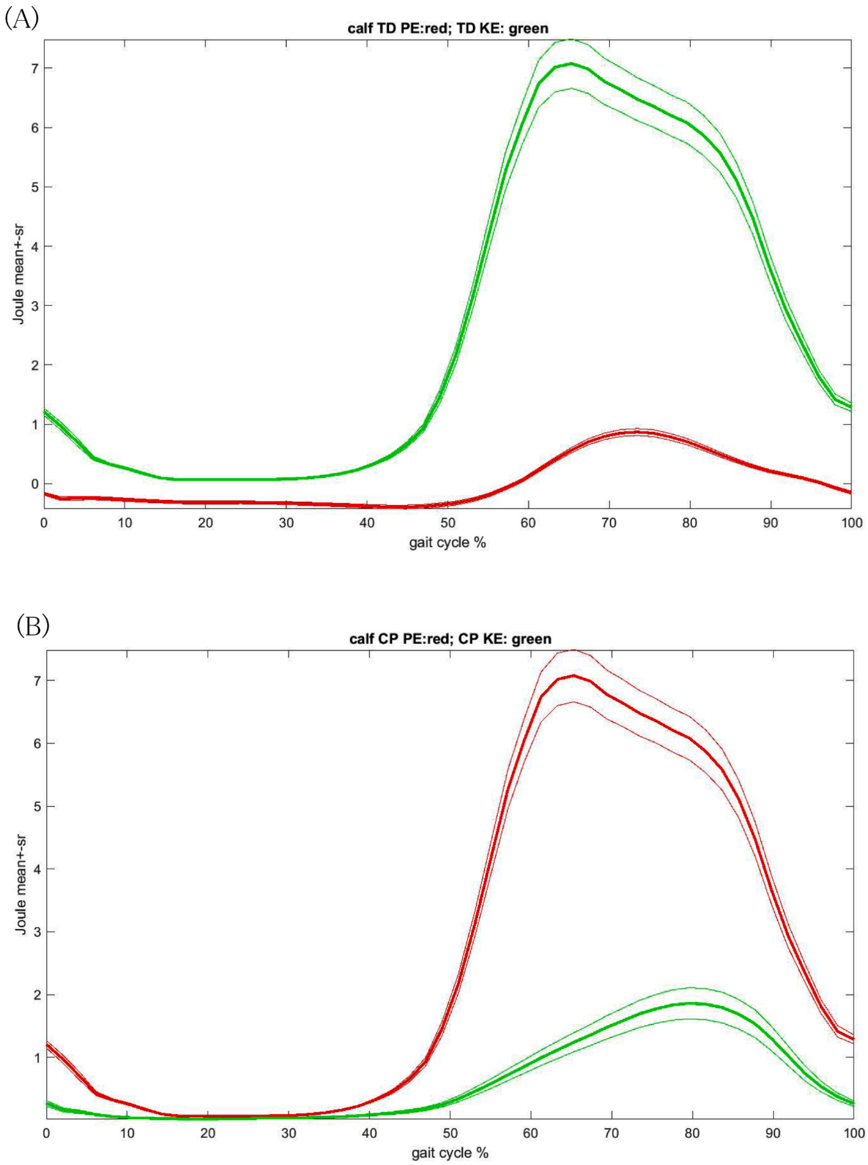


Fig. 3. The energy changes of the calf during gait in TD and CP groups. Note: Thick lines are means and thin lines standard errors. Rotative energy is neglected due to being too small compared with PE and KE. Using left and right sides together, the number of trials was 74 and 69 for CP and TD groups, respectively. When plotting potential energy, each trial has been shifted to the mean position as reference level. The kinetic and potential energy fluctuations were in phase (both up and down in the same time) in TD group as (A) and in CP group as (B).

only the thigh of the TD group had a significantly higher energy recovery coefficient than the CP group, which was 11.5% higher. There was no statistical difference in the foot and slight difference in the calf. This means that the TD group has better energy exchange efficiency than the CP group, especially in the thigh as in Table 5. The averaged energy fluctuations were plotted in Figs. 2–5. Using right and left sides together, the number of trials was 74 and 69 for CP and TD groups, respectively. It should be noted that when plotting potential energy, each trial has been shifted to the mean position as reference level to keep all curves consistently. As seen in the Figs. 2–5, two energy fluctuations in the thigh were out of phase (one up and another down), the calf were in phase, the foot did not show a clear fluctuation pattern. Thus, the thigh is the dominant segment of energy transfer during gait in compared with the calf and foot.

As reference and comparison between two groups, the joint angles or range of motion (RoM) in the sagittal plane are reported in Table 6. In general, the RoM in CP group is significantly smaller than in the TD group.

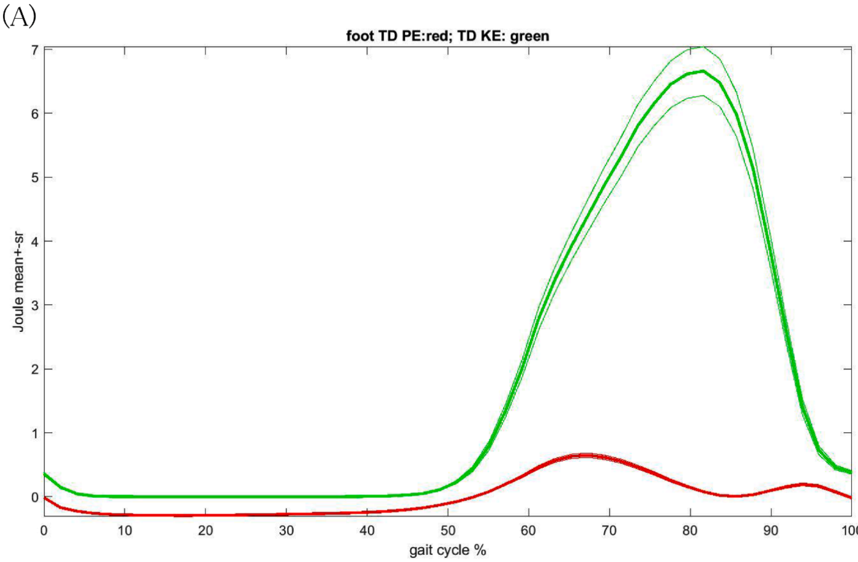
4. Discussion

4.1. Kinetic energy

The calculation of kinetic energy is based on the product of half the mass of an object and the square of its velocity. As there was no statistical difference in body mass between the two groups, it appears that the height is the primary cause of kinetic energy in both groups. This reasonably explains the difference in kinetic energy between the two sets of data. Ardestani et al. [6] and Majernik [7] have shown that speed can affect gait parameters, but our study saw differences in stride but not cadence between two groups.

Carcreff et al. [8] conducted a recent survey in 2020, which investigated the walking speed of young people with CP and TD in the laboratory and daily life and found that 60% of the CP group's daily walking speed was lower than the laboratory walking speed, and 60% of the TD group's daily walking speed was higher than the laboratory speed. Combined with the results of this experiment, it means that the difference in walking speed between the two groups of participants in daily life is more obvious. This suggests that the kinetic energy performance of CP children may be lower in daily life.

(A)



(B)

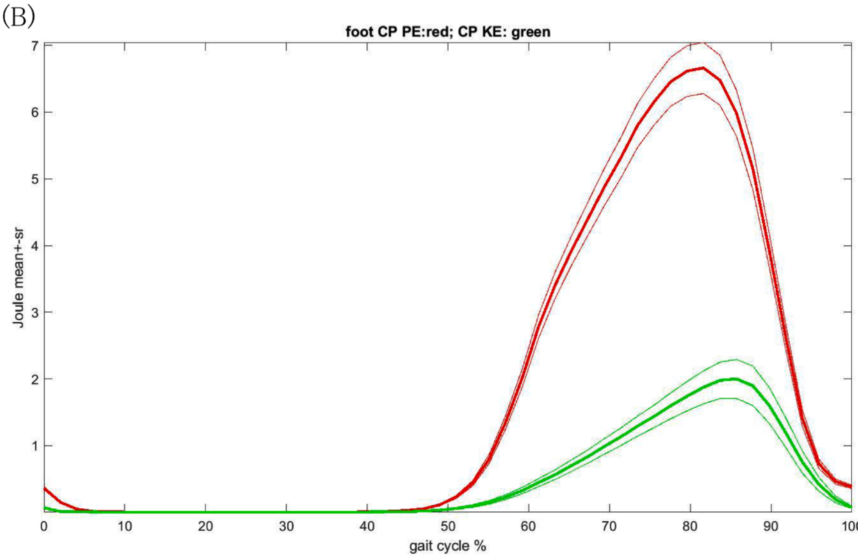


Fig. 4. The energy changes of the foot during gait in TD and CP groups. Note: Thick lines are means and thin lines standard errors. Rotative energy is neglected due to being too small compared with PE and KE. Using left and right sides together, the number of trials was 74 and 69 for CP and TD groups, respectively. When plotting potential energy, each trial has been shifted to the mean position as reference level. The kinetic and potential energy fluctuations were not clear pattern in terms of phase in TD group as (A) but were in phase (both up and down in the same time) in CP group as (B).

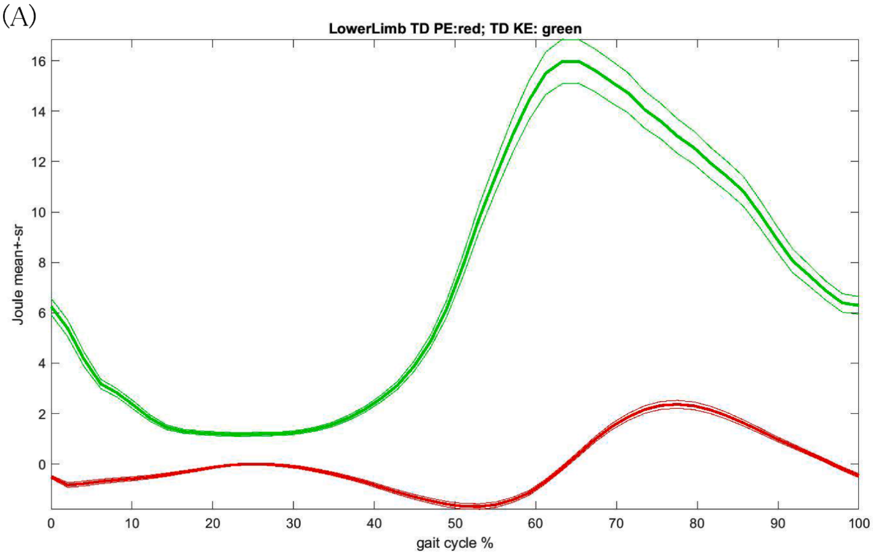
4.2. Potential energy

Potential energy is determined by the mass and the height of the limb centre of mass during movement, and the height of the centre of mass has a certain relationship with the joint movement angle of each part of the lower limb. Our findings confirm that whether the lower limbs are divided into parts or whole, the maximum average potential energy of the CP group is significantly smaller than that of the TD group. This means that in terms of the CoM height of the lower limbs reached during gait, the CP group is lower than the TD group, e.g. normalised max PE in TD lower limbs is 0.03 higher than CP as seen in Table 4. The reason for this may be related to the walking pattern of CP subjects. Chakraborty et al. [18] found that abnormal gait patterns in adolescents with CP may be accompanied by unstable postural control. Bar-Haim et al. [19] found that the mechanical efficiency of adolescents with CP is closely related to their balance ability. Mechanical efficiency defines the energy consumed to perform a certain amount of external work. Meanwhile, Zarkou et al. [20] found that the overall motor ability, balance ability, and gait performance of children with bilateral spastic cerebral palsy may be affected due to a certain degree of sensory processing dysfunction. Armand et al. [9] found that children with CP often exhibit complex movement disorders, leading to gait deviations. The experiment evaluated quantitative data on the gait of children with CP through clinical gait analysis (CGA), such as plantar pressure, kinematics, dynamics, and electromyography data, and found those common gait deviations in children with CP can be divided into gait patterns of spastic diplegia and spastic hemiplegia. These abnormal gait patterns can cause abnormal trajectories of the lower limbs during walking in children with CP. Bowal et al. [10] found an association between muscle spasms in children with spastic CP and sagittal movement of the lower limbs. Their study used normalized and non-normalized data to cluster the subjects' hip, knee, and ankle patterns, based on shape. There is a significant association between knee extension observed in this way and hamstring spasm. These studies provide possible reasons for the potential energy of the lower limbs of the CP group being significantly lower than that of the TD group.

4.3. Energy recovery coefficient

The concept of energy recovery coefficient has been used to evaluate the effectiveness of energy conversion for whole human body [5, 21–25], but there has been no research on the energy expenditure in the

(A)



(B)

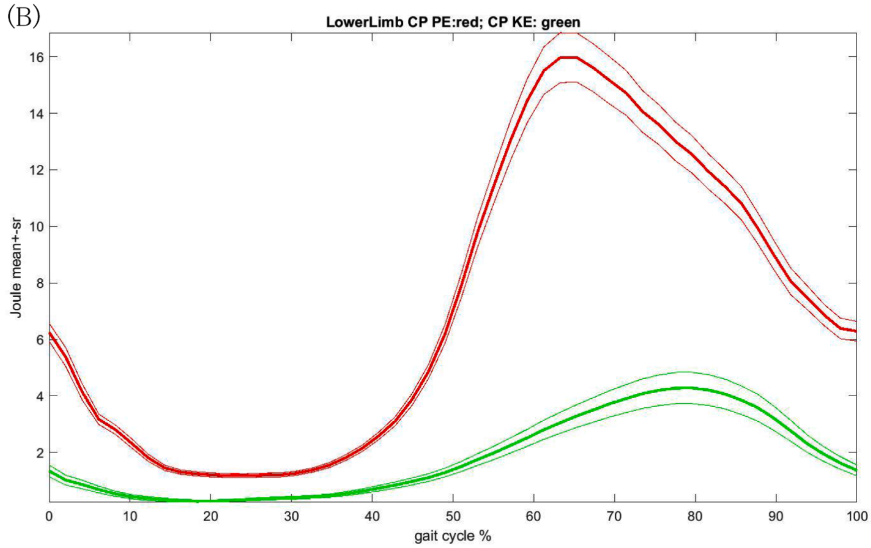


Fig. 5. The energy changes of the lower limbs including thigh, calf and foot during gait in TD and CP groups. Note: Thick lines are means and thin lines standard errors. Rotative energy is neglected due to being too small compared with PE and KE. Using left and right sides together, the number of trials was 74 and 69 for CP and TD groups, respectively. When plotting potential energy, each trial has been shifted to the mean position as reference level. The kinetic and potential energy fluctuations were not a clear pattern in terms of phase in TD group as (A) but were in phase (both up and down in the same time) in CP group as (B).

Table 6
Comparison of main joint ranges of motion between different groups.

Side			Mean	Std. error	95% Confidence Interval Lower bound	Upper bound
Left	AnkleAnglesXRoM	CP	21.651[a]	0.72	20.21	23.09
		TD	35.472[a]	0.75	33.96	36.99
	HipAnglesXRoM	CP	39.249[a]	0.85	37.54	40.96
		TD	49.293[a]	0.89	47.50	51.09
	KneeAnglesXRoM	CP	45.870[a]	0.61	44.65	47.09
		TD	65.666[a]	0.64	64.38	66.95
	PelivsAnglesXRoM	CP	7.636[a]	0.34	6.95	8.32
		TD	5.202[a]	0.36	4.48	5.92
Right	AnkleAnglesXRoM	CP	24.110[a]	0.80	22.49	25.73
		TD	59.404[a]	0.85	57.70	61.11
	HipAnglesXRoM	CP	42.293[a]	0.65	40.99	43.60
		TD	48.377[a]	0.68	47.00	49.75
	KneeAnglesXRoM	CP	46.074[a]	0.70	44.67	47.48
		TD	64.038[a]	0.73	62.56	65.52
	PelivsAnglesXRoM	CP	7.586[a]	0.29	6.99	8.18
		TD	4.664[a]	0.31	4.04	5.29

Note: all $p < 0.0001$. X is flexion and extension in the sagittal plane.
[a] Based on modified population marginal mean.

thigh, calf and foot, nor in CP or TD groups. According to the obtained results, the energy recovery coefficient of the TD group was significantly higher than that of the CP group from the resultant view of the lower limbs. From a segment point of view, the recovery coefficient of the thigh of the CP group was significantly lower than that of the TD group, but either no significant difference or slight difference was found in the foot and the calf. During walking, higher energy conversion efficiency is required in the thigh with heavier weight. In addition to the energy consumed by the walk itself, the calf and foot may need to use more energy to maintain walking balance. It can be seen from the Figs. 2–5 of energy changes in the gait cycle, compared to the CP group, the out-of-phase changes of the kinetic energy and potential energy of the TD group can make energy transfer more effective. The peaks or valleys of the kinetic energy were reasonably matched with the valleys or peaks of the potential energy in the TD group, especially in the thigh, but not in the CP group.

The higher the value of the energy recovery coefficient, the less effort subjects make during walking [5]. In the literature, Bennett et al. researched the movement of the centre of mass and energy conversion during walking of children with CP and found that the energy conversion efficiency of children with CP was lower than that of TD children [21], but they did not look into the lower limb segments. To our best knowledge, analysing the energy recovery coefficient of children with CP and TD in lower limb segments is a preferred approach to identify the barrier to more efficient energy transfer.

The results of energy exchanges shown that the pendulum principle has been used mainly in thigh during gait and TD group is better than the CP group, while the pendulum effects are not significantly seen in the calf and foot during gait.Eqs. (1)–(4)

5. Limitation

Although some interesting findings have been obtained, the limitation of this study is that the types of CP of the subjects included two only and each took small sample size. When the CP group was selected, it was only criteria that the participants could walk independently without any aid. Therefore, future studies could be considered for specific type of CP groups if the data would be available.

6. Clinical relevance

Since there is currently no analysis of the lower limbs' energy recovery coefficient of children with CP and TD, the results of this research study can be regarded as a supplement to this new field. The energy recovery coefficient can be used as a clinical evaluation of the rehabilitation results of children with CP, which has universal significance.

The energy recovery coefficient is mainly assessed by the kinetic and potential energy fluctuations in phases, e.g. in phase or out of phase, rather than by walking speed and stride length. Lower energy transfer in CP is mainly caused by their poor segments' coordination. Therefore, training for segments' coordination could be a way to improve walking efficiency.

7. Conclusion

The main purpose of this study was to analyse the energy changes of the thigh, calf and foot in the children with CP in compared with TD children during gait. Thus, the mechanical energy and energy recovery coefficient were calculated and compared for the two groups.

From the results, it was found that the energy of the lower limbs during walking in the CP group was significantly less than that of the TD group in terms of kinetic energy and potential energy. The more important finding is that the energy recovery coefficient of the thigh or whole lower limbs of the CP group was significantly lower than that of the TD group while the energy recovery coefficients of the foot and the calf for the two groups were similar.

In summary, the results of this project can be used to evaluate the rehabilitation results of children with CP. The higher the energy recovery coefficient, the higher the efficiency in the energy exchange of the kinetic and potential energies during gait, i.e., the easier the walking. As there is no other research investigating energy recovery coefficient of the lower limbs of children with CP, this report may be a good starting point for research in this area.

Funding information

None

Ethical note

A waiver of ethical approval. As this study extracted the data from the existing database without contacting participants, the school ethical committee granted the waiver of ethical application. The lab is on the base of a hospital where there is a general ethical approval for data collection and subjects had signed written consent forms when they attended the original data collection.

CRediT authorship contribution statement

Wei Hua: Data curation, Formal analysis, Investigation, Writing – original draft. **Sadiq Nasir:** Data curation, Investigation. **Graham Arnold:** Data curation, Project administration. **Weijie Wang:** Conceptualization, Formal analysis, Methodology, Software, Supervision, Visualization, Writing – review & editing.

Declaration of Competing Interests

None declared.

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