ORIGINAL ARTICLE

European Archives of Medical Research

DOI: 10.14744/eamr.2025.32559
Eur Arch Med Res 2026;42(2):133–138

Impact of Single-Event Multilevel Surgery on Energy Expenditure and Gait in Children With Cerebral Palsy

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ABSTRACT

Objective: Pre-pubertal cerebral palsy (CP) patients, particularly those classified as gross motor function classification system (GMFCS) grade II, often develop fixed musculoskeletal contractures that impair gait efficiency and increase energy expenditure. Among available treatment options, single-event multilevel surgery (SEMLS) offers the advantage of addressing multiple deformities in a single operative session, potentially leading to more efficient functional recovery and improved mobility. This study aimed to evaluate the effects of SEMLS on gait characteristics and walking energy expenditure in pre-pubertal children with spastic CP.

Materials and Methods: This study included patients aged 8–13 years who underwent SEMLS between November 2016 and September 2017. All participants had flexion and adduction contractures of the hip, a popliteal angle >50°, and equinus deformity, and were able to walk with or without support. Following long leg plaster cast immobilization for 6 weeks post-surgery, all patients received physical therapy. Three-dimensional gait analysis and walking energy expenditure (oxygen cost) were assessed one month before and 8–12 months after surgery.

Results: Post-operatively, there was a significant reduction in walking energy expenditure, despite no significant change in resting energy expenditure. Although not statistically significant, patients demonstrated an increased preferred walking speed. No significant differences were observed in mediolateral and vertical sacral displacement.

Conclusion: SEMLS significantly reduces walking energy expenditure and improves gait efficiency in pre-pubertal children with spastic CP (GMFCS grade II). These findings support SEMLS as an effective intervention, though larger studies with extended follow-up are needed to confirm long-term outcomes.

Keywords: Cerebral palsy, Children, Energy expenditure, Single-event multilevel surgery, Walking analysis

Cite this article as: Cevik K, Yilmaz DD, Altinkaya Z, Derici Yildirim D, Dal U, Milcan A. Impact of Single-Event Multilevel Surgery on Energy Expenditure and Gait in Children With Cerebral Palsy. Eur Arch Med Res 2026;42(2):133–138.

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Submitted: 17.05.2025 **Revised:** 04.08.2025 **Accepted:** 06.08.2025 **Available Online:** 03.06.2026

European Archives of Medical Research – Available online at www.eurarchmedres.org

INTRODUCTION

Cerebral palsy (CP) is a group of disorders caused by non-progressive brain injury occurring during early development when brain plasticity is high. CP has several types, including spastic, dyskinetic, ataxic, and mixed forms. In spastic CP, which is the most common, increased muscle tone typically affects the lower limbs (hip flexors, adductors, hamstrings, gastrocnemius), especially in spastic diplegia. According to which part of the brain damaged, whole upper and/or lower extremities can be affected by contractures resulting in a pathological gait pattern and deterioration in gross motor functions.[1] Children with CP often develop fixed contractures in affected muscle groups, leading to pathological gait patterns and reduced functional mobility. Conservative treatments such as physiotherapy, orthoses, and botulinum toxin injections may help manage symptoms but are often insufficient in cases with established deformities. In this context, Single-Event Multilevel Surgery (SEMLS) has become a preferred surgical approach. Unlike traditional orthopedic procedures that target isolated deformities across multiple operations, SEMLS addresses multiple musculoskeletal abnormalities in a single operative session. It aims to optimize gait mechanics, reduce cumulative anesthetic exposure, and shorten rehabilitation time. SEMLS is especially valuable in children with spastic diplegia, where bilateral lower extremity involvement is predominant.[2] Three-dimensional gait analysis (3DGA) serves as a key adjunct in both pre-operative planning and post-operative assessment, offering objective insight into dynamic gait parameters and supporting clinical decision-making.[3,4] Recent evidence further supports the efficacy of SEMLS in improving gait parameters.[5]

The primary aim of this study was to compare the walking energy expenditure and 3DGA of pre-puberty patients with CP who have lower leg extremity contractures and pertaining to level 2 according to Gross Motor Function Classification System (GMFCS), before and after multilevel muscle contracture release, including hip adductor and iliopsoas tenotomy, hamstring release and Achiloplasty. The findings of this study may provide additional insights into the effectiveness of multilevel release operation, by indicating any decrease in walking energy expenditure or improvement in their walking by 3DGA measurements after surgery.

MATERIALS AND METHODS

Participants

Eleven children who can walk on a treadmill without any assistance were selected from 30 CP children applied with SEMLS, and 3 were also excluded later, since they did not attend post-surgery measurements. Then, 8 children aged between 8 and 13 years with a confirmed diagnosis of bilateral spastic CP, involved in level 2 according to GMFCS were evaluated. All participants had been followed by the physical therapy and rehabilitation department for at least 1 year and had received treatments including botulinum toxin injections before being referred for surgical intervention. The study was a self-controlled clinical investigation which included energy expenditure and 3DGA measurements of each participant 1 month before surgery and 8–12 months after surgery. The inclusion criteria were the presence of any flexion and adduction contracture of the hip, a popliteal angle >50°, equinus deformity, ability to walk with/without external support, and oxygen mask tolerability. All subjects and their attendants were well informed about the protocols of the study and written informed consent was obtained. The Declaration of Helsinki was taken into consideration during the study, and the ethical approval of the study was granted from the Local Ethical Committee of Clinical Research (Date: March 23, 2017; Number: 2017/73). This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Surgery

All participants had bilateral adductor longus and iliopsoas tenotomies for hip deformities, z-plasty lengthening of the semitendinosus tendon, fractional lengthening of the semimembranosus and biceps femoris muscles to correct knee flexion deformities, and finally lengthening of the Achilles tendon by the Hoke method for the equinus deformity of the foot.

Surgical procedures were selected based on clinical indications, including the presence of fixed contractures identified through individual gait analysis and physical examination, such as excessive hip adduction, hamstring tightness, and equinus deformity that impaired functional ambulation. Surgical candidates were determined following a multidisciplinary evaluation involving orthopedic surgeons, rehabilitation specialists, and gait analysis teams. An abduction bar above-knee cast was applied for 6 weeks after surgery. Following the cast removal, knee-ankle-foot orthosis was applied and physical therapy initiated.[6]

Energy Expenditure Measurement

Resting and walking energy expenditure were assessed using a validated pediatric indirect calorimetry system, under standardized laboratory conditions (Vmax Spectra 29c. Yorba Linda, CA, USA). All devices were calibrated according to the manufacturer's instructions before each testing session to ensure accuracy. All measurements were done at 08:00–09:30 a.m., with temperature 20–24°C and humidity of 50%.[7] The standing height of subjects was measured by a stadiometer and their body compositions were determined by the bioelectrical impedance analysis method (Tanita BC-418 MA, Tanita Corporation, Japan). Participants were asked to fast overnight and avoid physical activity during the previous day. Resting energy expenditure (REE) was measured using a pediatric face mask that continuously collected respiratory gas data throughout the assessment. To reduce anxiety and improve cooperation, the presence of a parent and familiar objects was permitted, and the environment was quiet and private. Children were allowed to adapt to the mask for several minutes before beginning the 15-min REE protocol while lying calmly in a supine position. Preferred walking speed (PWS) was determined by having participants perform multiple walking trials on a fixed indoor track. Timing data were collected using motion sensors positioned along the walkway, and the average walking speed was calculated based on these repeated trials. Then, all subjects performed a familiarization protocol to treadmill (Viasys Health Care, USA) for at least 10 min.[7] Subjects rested until their heart rate stabilized within ±5 bpm of baseline.[8] Then, they were instructed to walk for 7 min at their PWS and allowed for holding the supporting bars of the treadmill while they were walking.

The first 10 min of REE measurement was accepted as a habituation period and excluded from analysis following prior pediatric studies using indirect calorimetry.[7] In terms of walking energy expenditure, the past 2 min of energy expenditure record was evaluated as a steady-state period and analyzed as averaging over 10 s intervals. The respiratory exchange ratio was also recorded to evaluate the intensity of exercise.[7]

Walking Analysis Protocol

The 3DGA of subjects was conducted by high-speed CCD cameras (BASLER Vision Technologies, Germany) while they were walking on a treadmill simultaneously with walking energy expenditure. A single marker to the sacrum (on skin), and 2 markers to the mid-points of heels (on shoes) were strapped to subjects for walking analysis. The sacral marker was strapped to the midpoint between two posterior superior iliac spine of patients (Plug-in Gait).

Gait parameters were recorded using a motion capture system, with reflective markers placed on anatomical landmarks. Recorded data were processed using dedicated motion analysis software. The 3DGA system was calibrated before each recording. Step width and stride frequency were evaluated as analyzing the vertical and mediolateral displacement of foot markers. The step width was determined as assuming the minimum level of vertical position of foot markers as heel-contact, then calculating the difference between mediolateral positions of foot markers. The system sensitivity was 0,001 mm.

Statistical Analysis

All data were analyzed using STATISTICA version 13.3 (TIBCO Software Inc., 2017). Descriptive statistics are presented as mean±standard deviation. The Shapiro–Wilk test was employed to assess the normality of the data. For within-subject comparisons between pre- and post-surgery values, the paired samples t-test was used for normally distributed variables, while the Wilcoxon signed-rank test was used for non-normal distributions. Statistical significance was set at $p<0.05$. In addition, effect sizes were calculated to assess the magnitude of observed differences: Cohen's d for parametric tests and rank-biserial correlation (r) for non-parametric tests.

RESULTS

8 CP children (5 boys and 3 girls) with a mean age of 10.88±1.73 years, pertaining to level 2 according to GMFCS, were included in this study. All patients had multilevel contracture release of their lower extremities. One of the patients was excluded from the study as he could not complete the walking analysis protocol. The anthropometric characteristics of subjects before and after surgery are listed in Table 1. Height is the only variable that differed significantly before and after surgery ($p<0.05$) (Table 1). VO_2 (L/min), which is the consumed O_2 in liters per minutes, was not significantly differed during resting condition ($p>0.05$). However; subjects have significantly higher VO_2 (L/min) values during walking before surgery compared to after surgery ($p<0.05$). Another expression for the walking efficiency, O_2 cost (mL/kg/m) which was calculated as normalizing walking O_2 expenditure (L/min) to body weight (kg) of patients, then dividing to PWS (m/min), has significantly decreased after surgery ($p<0.05$). The O_2 cost can provide a straight evaluation of O_2 expenditure per unit of walking distance by eliminating the effect of body weight differences among all participants (Table 2).

Table 1. Anthropometric characteristics of subjects before and after surgery

Variable	Pre-Surgery (mean±SD) n=7	Post-Surgery (8-12 months) (mean±SD) n=7	p
Height (cm)	132.76±11.43	137.63±11.46	<0.001
Body Weight (kg)	28.24±9.92	32.19±13.30	0.051
BMI (kg/m²)	15.90±2.90	17.17±4.20	0.226
Fat Percent (%)	20.35±5.61	21.88±5.76	0.433
Fat-Free Mass (kg)	22.02±4.42	26.22±8.38	0.112

BMI: Body Mass Index. All values are reported as mean±SD.

Table 2. Comparison of pre-surgery and post-surgery mean±SD values of various parameters

Parameter	Pre-Surgery (mean±SD) n=7	Post-Surgery (8-12 months) (mean±SD) n=7	Effect's size	p
VO_2 during resting (l/min)	0.20±0.05	0.20±0.06	d=0.00	0.811
VO_2 during walking (l/min)	0.53 (0.50-0.78)*	0.51 (0.37-0.72)*	r=0.89	0.012
O_2 cost during walking (ml/kg/m)	1.15±0.52	0.72±0.31	d=1.04	0.011
PWS (km/h)	1.39±0.49	1.56±0.45	d=0.36	0.093
Cadence (steps/min)	63.29±22.68	65.00±17.66	d=0.08	0.630
Step width (mm)	119.84±23.78	136.55±56.58	d=0.42	0.386
Displacement of sacral marker in mediolateral direction (mm)	26.84±7.99	22.38±6.07	d=0.62	0.157
Displacement of sacral marker in vertical direction (mm)	24.51±8.29	25.84±6.46	d=0.18	0.737

PWS: preferred walking speeds; VO_2: O_2 volume ; Values are reported as mean±SD except * indicates median (Q1-Q3).

In terms of gait variables of subjects, PWS (km/h) was not changed significantly after surgery compared to before surgery (p>0.05). Similarly, cadence (steps/minute) and step width (mm) were not increased significantly after surgery (p>0.05). The pre- and post-surgery differences in mediolateral and vertical displacement of the sacral marker were also not changed significantly after surgery (p>0.05) (Table 2).

Post-operative improvements were statistically significant and clinically meaningful for O_2 cost during walking (Cohen's d=1.04) and VO_2 during walking (rank-biserial r=0.89), both indicating large effect sizes.

Although changes in gait parameters such as PWS, cadence, step width, and sacral displacement were not statistically significant, these findings may reflect individual variability or limited post-operative observation duration.

DISCUSSION

This study evaluates energy expenditure while walking with 3DGA before and after multilevel release surgery in children with CP to evaluate its efficiency. Walking intensity significantly affects energy consumption, since quicker walking requires higher muscle performance and energy expenditure.[9] In their investigation, Rose et al.[10] discovered that CP patients used 2–3 times more energy walking in PWS than healthy volunteers. Our participants' mean walking energy consumption dropped considerably after SEMLS. Dahlbäck et al.[11] showed a 5% decreased oxygen demand per unit body weight after surgery. Another study of 135 CP patients found that O_2 consumption reduced 9% in orthopedic surgery (only) and 25% in orthopedic surgery with rhizotomy. The "Functional Assessment Query" showed a 38% improvement in gait pathology in the group who had both procedures.[12]

Increased body mass can raise the metabolic cost of walking, which may affect oxygen consumption. O_2 cost, which accounts for body weight differences, showed significant improvement post-operatively, consistent with prior literature.[9]

We observed that gait analysis improved our patients' mean PWS following surgery, although not significantly. Despite surgery, key gait metrics such as cadence and step width showed no significant short-term changes, aligning with earlier reports. We found that these individuals consumed less energy throughout walking tests without changing gait characteristics. However, after surgery, individuals prefer to walk faster with increased stride frequency and step width, reduced mediolateral sacral marker oscillation, and increased vertical oscillation. Individual adaptation time variation, a limited sample size, and inadequate statistical power may explain these factors' lack of statistical significance. Others may have modest dynamic gait alterations using knee-ankle-foot orthoses.

Only three markers were used in the gait investigation, limiting the biomechanical interpretation of hip, knee, and ankle joint kinematics. For functional gait evaluation, cadence and step width were prioritized. This technique met the study's main goal; however, future research should include comprehensive 3D gait analysis and reliability checks for broader interpretation.

Literature has reported mixed results on SEMLS effects on gait parameters in children with CP. Factors influencing short-term recovery after SEMLS have also been identified in recent studies, further highlighting the variability in patient outcomes.[13] Cadence improved in 18%[14-16] and walking speed in 24% of cases.[14,17-20] Dreher et al.[21] observed significant improvements in scores worsened at 1 year. Steinwender et al.[17] noted a gradual cadence decrease but improved walking speed. Kay et al.[22] and Graham et al.[23] reported minimal or no changes, particularly in older children. Similarly, Bernthal et al.[24] observed modest gains in walking speed and cadence following soft-tissue surgery, with unchanged pelvic kinematics but improved hip extension. Harvey et al.[25] documented mobility returning to baseline by 12 months, with improvements evident after 2 years. Cruz et al.[26] and Presedo et al.[27] reported no significant changes in walking speed after distal rectus femoris procedures, though knee kinematics improved.

Consistent with this, our study found no significant short-term change in sacral marker displacement. Rutz et al.[28] similarly reported no major gait parameter changes within 1–3 years of SEMLS, but notable improvements at 4–6 years. Svehlík et al.[29] and Dreher et al.[21] have emphasized the importance of mid- to long-term follow-up to accurately capture functional gains. These findings suggest that short-term assessments may underestimate the long-term benefits of SEMLS.

Our sacral marker results are consistent with previous studies showing minimal short-term changes in pelvic and hip joint kinematics after SEMLS.[16] McMulkin et al.[30] further reported that combining soft tissue and bony procedures can lead to greater improvements in gait metrics, underscoring the variability of outcomes depending on surgical approach and follow-up duration.

CONCLUSION

Taken together, the findings of this study contribute to the growing body of evidence supporting the metabolic benefits of SEMLS in children with spastic CP. While many previous studies have focused on long-term functional or kinematic improvements, our study uniquely highlights a significant reduction in walking energy expenditure shortly after surgery, despite the absence of statistically significant changes in gait parameters such as PWS, cadence, and step width. These results suggest that improved energy efficiency may serve as an early and sensitive indicator of surgical benefit and underscore the importance of incorporating both gait analysis and metabolic assessments in post-operative evaluation.

This study has several limitations that should be considered when interpreting the findings. First, the sample size was small, as only a limited number of patients were eligible and tolerated the procedures, particularly the energy expenditure testing using a face mask. Second, the follow-up period was relatively short, which may have precluded the detection of long-term functional or kinematic improvements. Third, the gait analysis used only three reflective markers and a limited number of cameras, which may have restricted the accuracy and comprehensiveness of joint kinematic data.

DECLARATIONS

Ethics Committee Approval: The study was approved by Mersin University Ethics Committee (No: 2017/73 Date: 23/03/2017).

Informed Consent: Written informed consent was obtained.

Conflict of Interest: The authors declare that there is no conflict of interest.

Funding: The authors received no financial support for the research and/or authorship of this article.

Use of AI for Writing Assistance: We disclose that we don't use artificial intelligence (AI).

Authorship Contributions: Concept – KC; Design – KC; Supervision – AM; Materials – DDY; Data collection &/or processing – ZA; Analysis and/or interpretation – DDYıldırım; Literature search – KC; Writing – KC; Critical review – UD.

Peer-review: Externally peer-reviewed.

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