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Are Electromyography Data a Fingerprint for Patients with Cerebral Palsy (CP)?

Mehrdad Davoudi ^{1,*} , Firooz Salami ¹ , Robert Reisig ¹, Dimitrios A. Patikas ² , Nicholas A. Beckmann ¹, Katharina S. Gather ^{1,3} and Sebastian I. Wolf ¹ 

¹ Clinic for Orthopaedics, Heidelberg University Hospital, Schlierbacher Landstr. 200a, 69118 Heidelberg, Germany; firooz.salami@med.uni-heidelberg.de (F.S.); robert.reisig@med.uni-heidelberg.de (R.R.); nicholas.beckmann@med.uni-heidelberg.de (N.A.B.); katharina.gather@umm.de (K.S.G.); sebastian.wolf@med.uni-heidelberg.de (S.I.W.)

² Laboratory of Neuromechanics, School of Physical Education and Sports Science at Serres, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece; dpatikas@auth.gr

³ Department for Pediatric Orthopedics, University Hospital Mannheim, Theodor-Kutzer-Ufer 1-3, 68166 Mannheim, Germany

* Correspondence: mehrdad.davoudi@med.uni-heidelberg.de; Tel.: +49-06221-56-26724

Abstract: This study aimed to first investigate changes in electromyography (EMG) patterns after multilevel surgical treatment in patients with cerebral palsy (CP) and then to assess the connection between the measure of EMG and motor control indices and surgery outcomes. We analyzed retrospective EMG and gait data from 167 patients with CP before and after surgery and from 117 typically developed individuals as a reference group. The patients underwent at least one soft tissue surgery on their shank and foot muscles. Using Repeated Measures ANOVA, we examined the norm-distance (ND) of the kinematics, kinetics, and EMG patterns, in addition to the Kerpape-Rennes EMG-based Gait Index (EDI), EMG Profile Score (EPS), and Walking Dynamic Motor Control Index (DMC) before and after surgery. Participants were divided into different response groups (poor, mild, and good gait quality) according to their pre- and post-treatment Gait Deviation Index (GDI), using the K-means-PSO clustering algorithm. The gait and EMG indices were compared between the responders using the nonparametric Mann–Whitney test. The ND for all kinematics and kinetics parameters significantly improved (p -value < 0.05) after the surgery. Regarding EMG, a significant reduction was only observed in the ND of the rectus femoris (p -value < 0.001) and soleus (p -value = 0.006). Among the indices, DMC was not altered post-operatively (p -value = 0.88). Although EDI and EPS were consistent across responders with a similar pre-treatment gait, a higher DMC was significantly associated with a greater improvement, particularly in patients with poor gait (p -value < 0.05). These findings indicate systematic changes in the EMG of patients with CP following surgery, which can also be demonstrated through indices. DMC is a measure that can potentially serve as a partial predictor of outcomes, particularly in patients with poor pre-operative gait. Future research should investigate the effects of different surgical strategies on the improvement of these patients.

Keywords: cerebral palsy; orthopedic surgery; EMG; motor control; clustering



Academic Editors: Federica Verdini, Alessandro Mengarelli, Andrea Tigrini, Francesca Lunardini and Jesús Tornero

Received: 12 December 2024

Revised: 13 January 2025

Accepted: 14 January 2025

Published: 14 January 2025

Citation: Davoudi, M.; Salami, F.; Reisig, R.; Patikas, D.A.; Beckmann, N.A.; Gather, K.S.; Wolf, S.I. Are Electromyography Data a Fingerprint for Patients with Cerebral Palsy (CP)? *Appl. Sci.* **2025**, *15*, 766. <https://doi.org/10.3390/app15020766>

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1. Introduction

Cerebral Palsy (CP) is the most common cause of physical disability in childhood and profoundly impacts development [1] and, notably, the ability to walk [2]. The global prevalence of CP varies from 1.6 to 3.3 per 1000 live births [3]. In addition to biomechanical

reasoning, understanding muscle activation patterns during gait with CP is essential for enhancing clinical decision-making and treatment outcomes.

A key question that arises in this context is whether the electromyogram (EMG) remains consistent as a “fingerprint” in patients with CP following orthopedic surgery. Visually inspecting pre- and post-operative EMG signals in patients with CP, Gueth et al. [4] answered this question as a ‘yes’, indicating that EMG is robust to surgery. Therefore, they proposed the idea that we do not need to measure the EMG after the operation. However, the reliance on a limited sample size and the subjective interpretation of raw EMG signals are two main limitations of their study. Eliminating subjectivity, particularly in the context of CP, where EMG patterns are complex and patient-specific, is crucial to ensure that conclusions are scientifically robust and applicable across diverse populations. Employing objective methods, such as signal processing and pattern recognition, minimizes bias, enhancing data precision and reliability. Systematic EMG analysis validates its robustness post-surgery, offering clinicians more accurate tools for assessing long-term outcomes in patients with CP. Patikas et al. further explored pre- and post-treatment EMG patterns by monitoring 34 patients with CP, focusing on changes in the EMG signal envelopes rather than raw signals [5]. They observed a systematic improvement in the EMG of shank muscles (soleus, tibialis anterior, and lateral gastrocnemius) after a single-event multilevel surgery (SEMLS). However, the reported changes compared to kinematics and kinetics were relatively small. The majority of the patients in their study had equinus foot deformity with a history of calf muscle lengthening surgery, indicating the significant impact of shank soft tissue surgery on EMG in patients with CP. These findings align with other studies that indicated muscle activation patterns, as well as their recruitment in patients with CP, may change after an intervention [6–8]. Consequently, they concluded that EMG can describe the clinical condition of the patient before and after orthopedic surgery, and it can be considered for better clinical decision-making, such as the approach developed by Reinbolt et al. [9] to predict the results of rectus transfer surgery.

The suggestion from Patikas et al. [5], which served as the main motivation for the current study, was to conduct a controlled study with a larger population and more homogeneous surgical treatment. They argued that employing such standardized approaches could help clarify the pre-operative compensatory mechanisms present in patients, ultimately improving the prediction of surgical intervention outcomes. Nonetheless, there remains a need for the development of new analytical methods to interpret EMG signals effectively in a clinical context. Moreover, the subjective evaluation of the pre-operative motor control status’ impact on surgical outcomes, in conjunction with CP biomechanics, constitutes a notable gap in the extant literature warranting attention.

Using clustering analysis, Davoudi et al. [10,11] established an association between the pre-operation activity of muscles in patients with CP and their response to the surgery. Moreover, they introduced a simple index as the ratio between the activity of the rectus femoris and gastrocnemius lateralis muscles as a predictor of the chance of improvement in patients with a crouch gait. Kinematic indices such as the Gait Deviation Index (GDI) [12] and the Gait Profile Score (GPS) [13] are two measures of gait quality whose applicability in the assessment of gait with CP has already been reported in the literature [14–17]. The Kerpape-Rennes EMG-based Gait Index [18], referred to as the EMG Deviation Index (EDI) in this study, and the EMG Profile Score (EPS) [19] are two EMG-based measures calculated using the same methodology as the GDI and GPS, respectively. EDI quantifies global muscle activity based on the Euclidean distance between a patient’s EMG pattern and that of typically developing (TD) subjects using principal component analysis. Scores equal to or above 100 indicate normal gait, with a decrease of 10 points indicating a deviation of one standard deviation (SD) from TD. Additionally, to assess deviations from the norm for

individual muscle groups independently, the EPS was calculated based on the mean of the root mean square error (RMSE) for each muscle during the gait, providing a score without units. While these are validated measures [20], there is no study on the use of EMG indices in the CP population.

Although EDI and EPS can describe biomechanics by considering patterns, they are relatively weak in presenting the degree of motor involvement of the patient. To address this limitation, Schwartz et al. introduced the Walking Dynamic Motor Control Index (Walk-DMC) to clinically assess the effect of altered neuromuscular control on treatment outcomes in patients with CP [21]. A higher DMC suggests better motor function, with 100 being the average DMC for TD individuals and 10 points representing one standard deviation from typical development outcomes. The observed DMC was significantly associated with the response to treatment, second only to the pre-treatment level of GDI. However, the treatment in their study included various interventions such as surgery, physical therapy, and selective dorsal rhizotomy. Additionally, the influence of DMC level on individuals with similar gait quality prior to treatment was not investigated. Therefore, it remains unclear how DMC can be helpful for predicting the results of surgery in patients with CP.

The primary aim of this study was to investigate the effect of SEMLS on the EMG and gait kinematics of patients with CP. To ensure more homogeneous surgical management across the cohort, we focused on patients who underwent soft tissue surgery on their shank and foot muscles, in addition to potentially other more proximal surgeries. We also evaluated the applicability of EMG indices as global measures for assessing surgical outcomes in the CP population. To the best of our knowledge, this is the first study to measure EDI and EPS in patients with CP. Additionally, we assessed the relationship between motor control (DMC) and surgery outcomes for subgroups with the same level of GDI.

Our first hypothesis is that while EMG patterns, as a biomechanical aspect of muscle activity, will change following surgery, motor control remains stable and independent of specific gait patterns. Our second hypothesis is that DMC is resilient to biomechanical corrections after surgery and that pre-treatment DMC levels could potentially serve as a predictor for improvement following SEMLS in CP patients.

These hypotheses are clinically significant because they could offer insights into how EMG and motor control measures can be used to predict surgical outcomes, ultimately guiding more personalized treatment strategies for patients with CP.

2. Materials and Methods

2.1. Ethics Statement

This study was approved by the local Ethical Committee, “Medical Faculty, Heidelberg University (no: S-243/2022)”.

2.2. Participants

The data analyzed in this retrospective study were part of a larger database established at the local University Hospital in the years 2000–2022 when retrieval was stopped. Only personnel who had regular legal access to the medical records retrieved patient data, collected it, and anonymized it. After this step, individual participants could no longer be identified. They retrieved patient data from the records on 15 November, 1 December, and 13 December 2022, and anonymized it in the same year on 28 December.

The database was filtered for patients with CP with at least two consecutive examinations in the local gait laboratory with orthopedic surgery in between. Examinations that did not show high-quality EMG data were excluded, and surgeries had to address gait disorders caused by CP. If multiple examinations were available, the dates closest to the surgery were selected. The first examination (E1) was conducted before the operation,

and the second examination (E2) was typically conducted one year after the operation. Therefore, E1 and E2 pertain to the same individuals evaluated at different time points. For patients with hemiplegia, only data from the affected side were considered.

Further primary inclusion criteria encompassed gait and clinical data for each examination, walking barefoot without assistive devices, and classification as Gross Motor Function Classification System (GMFCS) level I or II. Usually, the surgeries involved multiple procedures on different levels (hip, thigh, shank, and feet). If multiple surgeries were performed on different dates between the two examinations, all procedures were included in this study as they could be relevant for the second examination. Following the recommendation of Patikas et al. [5], to ensure a more homogeneous approach to surgical treatment, we focused on patients who, among other procedures, underwent soft tissue surgery on muscles located at the shank and foot level. For 91% of patients, this involved at least one surgery on the triceps surae muscle, such as the Baumann Procedure [22] (46%), Strayer Procedure [23] (46%), or Achilles Tendon Lengthening [24] (17%). Additionally, there were some muscle transfer surgeries, such as tibialis anterior transfer (13%) and tibialis posterior transfer (9%), and multiple muscle lengthening procedures, such as flexor digitorum longus lengthening (3%). In most cases, the surgery included further procedures on another level, i.e., legs and feet. The most prevalent additional procedures were femoral derotation (78%), bony foot procedures (38%), rectus transfer (30%), and hamstring lengthening (28%).

Furthermore, according to [5], we chose to assess only the more involved side in each patient to maintain homogeneity regarding severity. This was defined as the side that underwent surgery, and in cases of bilateral involvement, the side with the lower GDI was selected for further analysis. Following the application of these criteria, 167 patients were recruited, along with 117 TD individuals serving as the reference group. Table 1 presents the characteristics of this study's participants.

Table 1. Demographic and descriptive data of the participants at their first (E1) and second (E2) examinations and also TD individuals.

	E1 (n = 167) Pre-Operative Examination	E2 (n = 167) Post-Operative Examination	TD (n = 117)
Age (years)	15.86 ± 8.6 (5.3–49.5)	18.1 ± 8.9 (6.9–54.2)	21.7 ± 12.3 (6.0–46.0)
Height (cm)	149.1 ± 18.5 (105.0–194.0)	152.6 ± 18.2 (121.0–187)	161.9 ± 19.8 (108.0–195.0)
Body mass (kg)	43.68 ± 16 (14.6–87.3)	46.8 ± 17.3 (14.8–101.8)	66.4 ± 16.8 (19.0–91.0)
Sex (male/female)	84/83		58/59
CP type (diplegia/ hemiplegia)	148/19		
Interval between examinations (years)	2.3 ± 1.8 (0.8–13.5)		

2.3. Data Processing

The data recording and processing approach used in this study was the same as the one described in our recently published paper on rectus femoris EMG clustering [10].

All subjects walked barefoot at a self-selected speed along a lane 15 m in length during data acquisition. Kinematics and kinetics were recorded using a twelve-camera 3D motion analysis system (VICON, Oxford Metrics Limited, Yarnton, UK) operating at 120 Hz and using three force plates (Kistler Instruments Co., Vienna, Austria), respectively. The skin-mounted markers were applied according to the protocol of Kadaba et al. [25], and the plug-in-gait model was chosen to calculate the kinematics, kinetics, and spatiotemporal parameters of participants' gait. Subsequently, the parameters were determined for at least seven strides.

The EMG data were recorded from seven major lower-extremity muscles: rectus femoris, vastus lateralis, tibialis anterior, semimembranosus, biceps femoris, lateral gastroc-

nemius, and soleus, on both right and left legs, using myon 320 (Myon AG, Schwarzenberg, Switzerland). Bipolar surface adhesive electrodes (Blue Sensor, Ambu Inc., Glen Burnie, MD, USA) were placed on the targeted muscles, following the guidelines provided by SENIAM [26]. The distance between the electrodes was set at 2 cm [27]. To amplify the EMG signal, the Biovision EMG apparatus (Biovision Inc., Wehrheim, Germany) was utilized before 2013/2014 and via Delsys (Delsys Inc., Natick, MA, USA) after 2013/14, with a preamplification factor of $\times 5000$.

The raw EMG data were then band-pass filtered (Butterworth filter with a cutoff frequency of 20–350 Hz), rectified, and the signal smoothed (Butterworth low-pass filter with a cutoff frequency of 9 Hz), amplitude-normalized to the mean of signal, time-normalized within one gait cycle (101 datapoints), and eventually averaged across valid strides in Matlab (2018b, The MathWorks, Inc., Natick, MA, USA) [5]. The calculated envelopes were used for subsequent analysis.

To quantify the extent of deviation in a patient's EMG envelopes and gait parameters relative to a reference group, we calculated the norm-distance (ND) according to [5]. ND was defined as the absolute difference between a muscle's EMG envelope at the i -th data point belonging to the patient p (F_{pi}) and the mean value of the corresponding data point within that muscle for the reference group ($\bar{F}_{ni}$), divided by the respective standard deviation within the reference group (SD_{ni}), as expressed in Equation (1). The ND values for all 101 data points were averaged over a gait cycle for further analysis. Changes in the average ND ($\overline{ND}$) from the initial examination (E1) to the subsequent examination (E2) were regarded as indicative of the surgery's impact on the patient's EMG. A reduction in $\overline{ND}$ following the intervention suggested an improvement towards a pattern more similar to the reference group.

$$ND_i = \frac{|F_{pi} - \bar{F}_{ni}|}{SD_{ni}} \quad (1)$$

The same procedure was also employed to assess gait patterns in sagittal plane, including angles, moments, and power at the hip, knee, and ankle joints.

2.4. Gait and EMG Indices

EMG indices, including EDI [18], EPS [19], and Walk-DMC [21], were derived from the envelopes in accordance with the existing literature. An increase in EDI, along with a reduction in EPS, may signify improvement post-surgery. Moreover, a higher DMC indicates enhanced motor control function in the patient. Additionally, GDI [12] and GPS [13], as measures of gait quality, were evaluated in both E1 and E2 for the patients. A higher GDI and a lower GPS are associated with reduced deviation from a typical gait pattern. All analyses for the extraction of parameters and indices were conducted using Matlab software (The MathWorks, Inc., USA).

2.5. Clustering

We utilized the same k-means-PSO clustering algorithm as in our previous study [10] to categorize patients into three different gait levels based on their GDI in each examination, pre- (E1) and post-operative (E2). By averaging the GDI of patients within each cluster, we classified the patients as having good, mild, and poor gait quality, corresponding to high, medium, and low mean GDI, respectively (Section 3). Figure 1 shows the clustering procedure applied to our database. The clustering algorithm was developed using Matlab, based on the details described in [10]. The algorithm was identical for both E1 and E2 populations. The number of clusters was determined by us in a supervised manner, set at 'n = 3'. This allowed us to track the changes in gait quality of the patients (Figure 1).

Although the patients in both E1 and E2 are the same (matched), their GDI values may differ due to the effects of the surgery (Figure 1A,B).

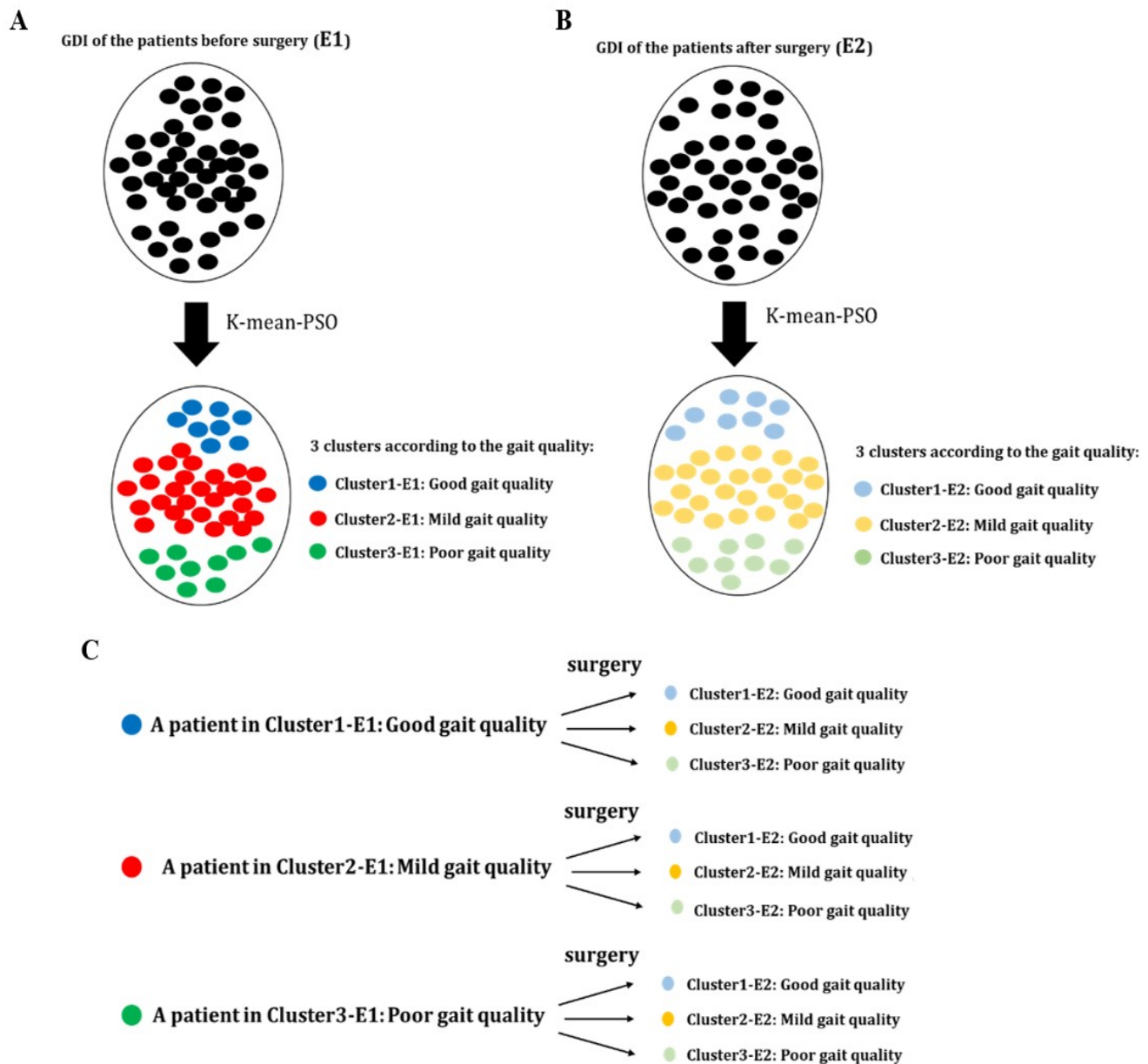


Figure 1. The clustering of the patients, (A) according to their pre-operation (E1) GDI, and (B) according to their post-operation (E2) GDI. (C) The possible responses of the patients to the surgery, identified within each cluster both pre- and post-operation.

Using this approach, we removed the effect of the pre-treatment level of GDI, which, according to [21], significantly influences the outcomes of surgery. Subsequently, we identified three groups of patients with the same pre-operative GDI level (E1). Each patient could have one of three possible responses to the intervention: good, mild, or poor, corresponding to being identified as Cluster 1, Cluster 2, or Cluster 3 post-operatively (E2) (Figure 1C). Furthermore, the specifics of the type and number of surgeries performed between E1 and E2 for different responders are examined to investigate any potential bias arising from the treatment approach on the responses and clustering outcomes. According to the surgical details described in Section 2.2, the most frequent proximal surgeries (femoral derotation, rectus transfer, and hamstring lengthening) and the main distal surgeries

(Baumann and Strayer procedures, Achilles tendon lengthening, and bony foot procedures) were considered for examination between the clusters.

2.6. Statistics

To compare the effect of the intervention on the ND of kinematics, kinetics, and EMG parameters (Sections 2 and 3) and on the indices outlined in Sections 2–4, Repeated Measures ANOVA was used. Further, for the muscles that showed a significant improvement (p -value = 0.05) in their ND post-treatment, we applied statistical parametric mapping (SPM, version: M.0.4.10, www.spm1d.org) implemented in Matlab [28] to assess the temporal changes in muscle activation patterns across the entire gait cycle. SPM(t) compares the data at each time point within the gait cycle, identifying significant differences between pre- and post-treatment measurements throughout the cycle. This approach, as described by Pataky et al. (2010) [28], allows for a detailed analysis of where changes in muscle activation occur, without reducing the data to specific phases of the gait cycle.

We applied the nonparametric Mann–Whitney test (p -value = 0.05) to compare the primary levels of the gait and EMG indices between the groups with the same condition in E1 and also to assess their changes from E1 to E2.

3. Results

The ND of all measured kinematics and kinetics parameters exhibited significant improvement (p -value < 0.05) post-surgery, as shown in Table 2. Regarding EMG, a significant reduction was only observed in the ND of the EMG for the rectus femoris (p -value < 0.001) and soleus (p -value = 0.006), as detailed in Table 3. While the gait indices (GDI and GPS) and EMG indices (EDI and EPS) demonstrated significant changes towards normal values from E1 to E2 (p -value < 0.001), the measure for motor control (DMC) showed no significant difference after the intervention (p -value = 0.88).

Table 2. Pre-(E1) and post-operative (E2) norm-distance of the kinematics and kinetics parameters and for GDI and GPS. ND: norm-distance.

Measure	Examination	Mean (SD)	95% Confidence Interval (Lower Bound–Upper Bound)	Sig.
ND ankle dorsiflexion (degree)	E1	3.36 (0.22)	2.93–3.78	<0.001
	E2	1.81 (0.07)	1.67–1.95	
ND ankle dorsiflexion moment (Nm/kg)	E1	2.07 (0.04)	1.99–2.15	<0.001
	E2	1.63 (0.04)	1.54–1.71	
ND ankle dorsiflexion power (W/kg)	E1	1.80 (0.06)	1.68–1.91	<0.001
	E2	1.29 (0.04)	1.21–1.38	
ND knee flexion (degree)	E1	3.24 (0.14)	2.96–3.52	<0.001
	E2	2.53 (0.12)	2.28–2.77	
ND knee flexion moment (Nm/kg)	E1	1.76 (0.06)	1.65–1.87	<0.001
	E2	1.55 (0.05)	1.44–1.66	
ND knee flexion power (W/kg)	E1	1.24 (0.03)	1.18–1.30	<0.001
	E2	1.11 (0.02)	1.07–1.16	
ND hip flexion angle (degree)	E1	1.81 (0.08)	1.66–1.97	<0.001
	E2	1.52 (0.07)	1.39–1.65	
ND hip flexion moment (Nm/kg)	E1	1.85 (0.05)	1.76–1.95	<0.001
	E2	1.54 (0.05)	1.45–1.64	
ND hip flexion power (W/kg)	E1	1.74 (0.04)	1.67–1.81	<0.001
	E2	1.55 (0.04)	1.47–1.63	
GDI	E1	58.51 (0.96)	56.61–60.42	<0.001
	E2	73.74 (0.92)	71.93–75.55	
GPS	E1	14.35 (0.35)	13.66–15.03	<0.001
	E2	9.73 (0.24)	9.27–10.20	

Table 3. Pre-(E1) and post-operative (E2) norm-distance of the EMG activity of muscles and for EDI, EPS, and DMC. ND: norm-distance.

Measure	Examination	Mean (SD)	95% Confidence Interval (Lower Bound–Upper Bound)	Sig.
ND rectus femoris	E1	1.51 (0.031)	1.45–1.57	<0.001
	E2	1.39 (0.028)	1.34–1.45	
ND vastus lateralis	E1	1.45 (0.03)	1.39–1.51	0.63
	E2	1.43 (0.034)	1.37–1.50	
ND tibialis anterior	E1	1.34 (0.027)	1.29–1.39	0.19
	E2	1.30 (0.025)	1.25–1.35	
ND gastrocnemius lateralis	E1	1.19 (0.022)	1.14–1.23	0.29
	E2	1.15 (0.025)	1.10–1.20	
ND soleus	E1	1.36 (0.028)	1.30–1.41	0.006
	E2	1.26 (0.025)	1.21–1.31	
ND biceps femoris	E1	0.95 (0.024)	0.91–1.00	0.76
	E2	0.95 (0.022)	0.90–0.99	
ND semimembranosus	E1	0.98 (0.027)	0.92–1.03	0.15
	E2	0.94 (0.023)	0.89–0.98	
EDI	E1	82.2 (0.36)	81.50–82.94	<0.001
	E2	83.84 (0.38)	83.10–84.59	
EPS	E1	73.60 (0.78)	72.06–75.15	<0.001
	E2	70.23 (0.75)	68.75–71.72	
DMC	E1	79.72 (0.66)	78.43–81.01	0.88
	E2	79.63 (0.64)	78.37–80.88	

SPM analysis revealed significant differences at specific phases of the gait cycle for the rectus femoris, approximately 20% (early stance) and 75% (mid-swing) (Figure 2A). For the soleus, significant differences were observed at the beginning (initial contact), around 50% (end of stance), and at the end (terminal swing) of the gait cycle between E1 and E2 (Figure 2B).

Initial clustering results provided in Table 4 indicate the mean and SD of the GDI for patients identified in each cluster at two assessment points (pre- and post-operation). Patients with the best and the poorest gait performance at E1 had an average GDI of 71.02 and 43.43, respectively. The same assigned gait conditions had an average GDI of 86.47 and 58.51 at E2. This illustrates the general effect of the surgery on improving gait, as evidenced by the increase in the mean GDI from 58.51 at E1 to 73.74 at E2. However, since individual responses varied, patients were categorized according to the change in their cluster post-operation. Tables 5–7 compare those with similar pre-operative gait, minimizing the influence of initial gait quality.

Table 4. Average GDI of the patients within each identified cluster pre- and post-operation, along with the assigned gait conditions.

Examination Time	Cluster	Average (SD) of GDI for the Patients in the Cluster	Assigned Gait Condition
E1 (pre-operation)	Cluster 1	71.02 (6.9)	Good
	Cluster 2	55.18 (3.0)	Mild
	Cluster 3	43.43 (5.0)	Poor
E2 (post-operation)	Cluster 1	86.47 (6.8)	Good
	Cluster 2	72.28 (3.3)	Mild
	Cluster 3	58.51 (6.7)	Poor

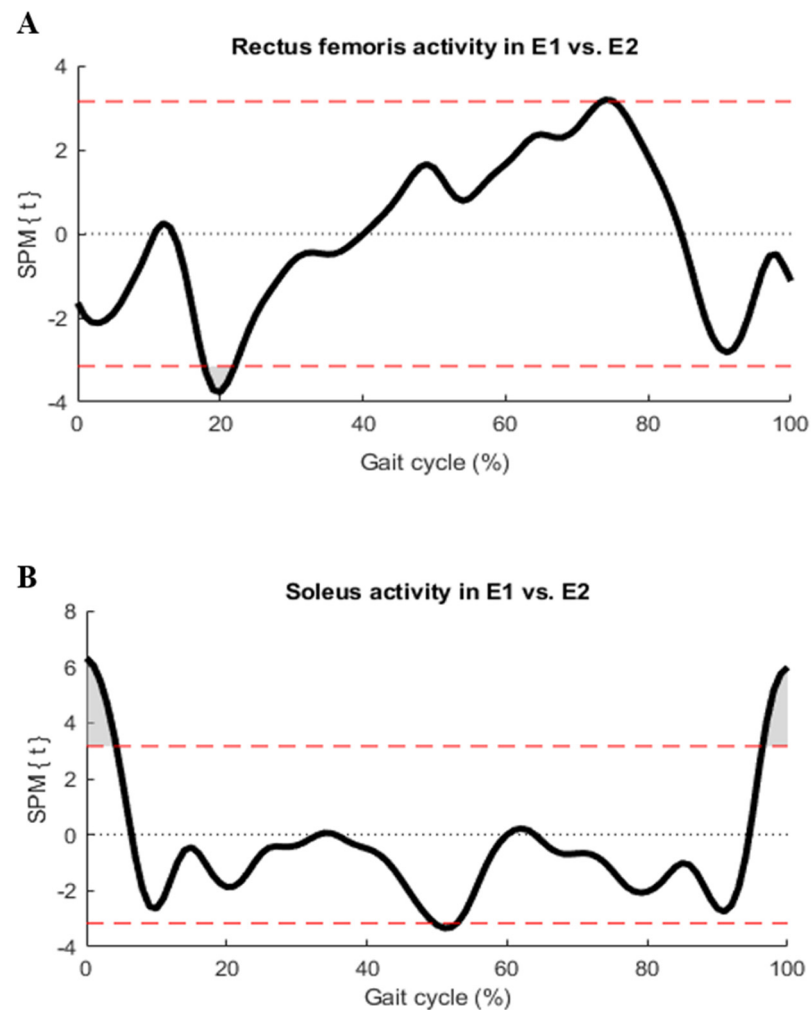


Figure 2. Results of SPM analysis highlighting differences in EMG patterns of rectus femoris (A) and soleus (B) muscles pre-operation (E1) and post-operation (E2) throughout the gait cycle. Dark areas indicate significant differences in activity.

Table 5. Comparative analysis of gait and EMG indices among participants with poor gait quality at baseline (E1) across responders according to their post-operation gait quality.

Variable	Gait Quality Condition Before Surgery (E1)	Gait Quality Condition After Surgery (E2)	No.	Mean (SD) in E1	Mean (SD) in E2	p-Value Between E1 and E2	p-Value Between Poor_to_Good and Poor_to_Mild in E1	p-Value Between Poor_to_Good and Poor_to_Poor in E1	p-Value Between Poor_to_Mild and Poor_to_Poor in E1
GDI	Poor	Good	10	42.27 (5.8)	86.21 (7.4)	<0.001	0.418	0.387	0.516
	Poor	Mild	22	43.98 (4.8)	72.55 (0.8)	<0.001			
	Poor	Poor	11	43.56 (5.2)	57.01 (8.0)	<0.001			
GPS	Poor	Good	10	20.92 (3.4)	6.93 (1.2)	<0.001	0.392	0.453	0.422
	Poor	Mild	22	19.96 (2.7)	9.54 (0.98)	<0.001			
	Poor	Poor	11	20.2 (2.9)	14.43 (3.4)	<0.001			
EDI	Poor	Good	10	83.49 (3.4)	84.49 (5.3)	0.137	0.184	0.057	0.312
	Poor	Mild	22	81.69 (2.5)	85.03 (0.9)	<0.001			
	Poor	Poor	11	80.96 (3.3)	82.62 (3.7)	0.147			
EPS	Poor	Good	10	70.8 (6.3)	69.08 (10.9)	0.126	0.162	0.103	0.437
	Poor	Mild	22	74.33 (5.6)	67.74 (1.6)	<0.001			
	Poor	Poor	11	75.51 (7.6)	71.86 (7.5)	0.18			
DMC	Poor	Good	10	84.22 (6.4)	85.37 (9.1)	0.339	0.256	<0.001	0.004
	Poor	Mild	22	78.64 (7.2)	79.02 (1.8)	0.387			
	Poor	Poor	11	71.66 (6.9)	72.75 (6.5)	0.447			

Table 6. Comparative analysis of gait and EMG indices among participants with mild gait quality at baseline (E1) across responders according to their post-operation gait quality.

Variable	Gait Quality Condition Before Surgery (E1)	Gait Quality Condition After Surgery (E2)	No.	Mean (SD) in E1	Mean (SD) in E2	<i>p</i> -Value Between E1 and E2	<i>p</i> -Value Between Mild_to_Good and Mild_to_Mild in E1	<i>p</i> -Value Between Mild_to_Good and Mild_to_Poor in E1	<i>p</i> -Value Between Mild_to_Mild and Mild_to_Poor in E1
GDI	Mild	Good	15	55.99 (3.7)	86.55 (4.9)	<0.001	0.09	0.374	0.128
	Mild	Mild	21	54.41 (3.1)	73.05 (3.4)	<0.001			
	Mild	Poor	21	55.39 (2.4)	58.9 (7.2)	<0.001			
GPS	Mild	Good	15	14.56 (1.3)	6.9 (0.8)	<0.001	0.065	0.379	0.149
	Mild	Mild	21	15.19 (1.2)	9.49 (0.8)	<0.001			
	Mild	Poor	21	14.77 (0.9)	13.72 (3.2)	<0.001			
EDI	Mild	Good	15	83.41 (4.4)	84.55 (4.9)	0.291	0.138	0.14	0.448
	Mild	Mild	21	81.61 (4.7)	83.21 (5.8)	0.202			
	Mild	Poor	21	81.99 (4.0)	83.42 (4.5)	0.194			
EPS	Mild	Good	15	71.35 (8.9)	69.64 (10.2)	0.294	0.183	0.207	0.479
	Mild	Mild	21	74.82 (10.3)	71.62 (12)	0.172			
	Mild	Poor	21	73.78 (8.8)	70.85 (8.9)	0.191			
DMC	Mild	Good	15	81.91 (7.3)	79.98 (7.5)	0.252	0.112	0.293	0.225
	Mild	Mild	21	78.14 (10.3)	78.32 (8.2)	0.465			
	Mild	Poor	21	80.07 (8.5)	80.5 (7.1)	0.445			

Table 7. Comparative analysis of gait and EMG indices among participants with good gait quality at baseline (E1) across responders according to their post-operation gait quality.

Variable	Gait Quality Condition Before Surgery (E1)	Gait Quality Condition After Surgery (E2)	No.	Mean (SD) in E1	Mean (SD) in E2	<i>p</i> -Value Between E1 and E2	<i>p</i> -Value Between Good_to_Good and Good_to_Mild in E1	<i>p</i> -Value Between Good_to_Good and Good_to_Poor in E1	<i>p</i> -Value Between Good_to_Mild and Good_to_Poor in E1
GDI	Good	Good	30	72.06 (7.1)	86.53 (7.8)	<0.001	0.132	0.345	0.412
	Good	Mild	30	70.08 (7)	71.55 (3.1)	0.023			
	Good	Poor	7	70.62 (6.7)	59.72 (3.4)	0.002			
GPS	Good	Good	30	9.85 (1.7)	6.94 (1.1)	<0.001	0.15	0.304	0.488
	Good	Mild	30	10.31 (1.7)	9.83 (0.8)	0.021			
	Good	Poor	7	10.29 (1.6)	13.35 (1)	0.002			
EDI	Good	Good	30	82.45 (6.6)	85.01 (5)	0.044	0.381	0.231	0.394
	Good	Mild	30	82 (5.4)	82.78 (5.2)	0.343			
	Good	Poor	7	83.73 (3.5)	82.11 (3.7)	0.311			
EPS	Good	Good	30	73.71 (13.5)	68.13 (9.5)	0.035	0.36	0.245	0.319
	Good	Mild	30	74.25 (12.7)	72.19 (11.1)	0.278			
	Good	Poor	7	70.25 (7.1)	73.36 (7.3)	0.356			
DMC	Good	Good	30	82.68 (6.9)	80.91 (7.7)	0.141	0.038	0.041	0.495
	Good	Mild	30	78.95 (9.7)	79.8 (8.6)	0.37			
	Good	Poor	7	78.08 (4)	76.28 (8.1)	0.268			

For patients with severe pre-operative gait conditions (Table 5), all three responder groups experienced significant GDI improvements: 44, 30, and 14 units for good, mild, and poor responses, respectively. While gait and EMG indices (EDI and EPS) at E1 were consistent across these responders, DMC was significantly lower for patients with a poor response (Poor_to_Poor) compared to those with a good response (Poor_to_Good, 72.75 vs. 85.37, *p*-value < 0.001) and a mild response (Poor_to_Mild, 72.75 vs. 79.02, *p*-value = 0.004). EDI and EPS also improved from E1 to E2 across all responders, particularly for the mild ones (Poor_to_Mild, *p*-value < 0.001).

Additionally, the improvement in gait for patients with moderate pre-operative gait issues was significant (Table 6). The mean DMC for the best responders (Mild_to_Good) was higher than that of the other two groups at E1, and the levels of EDI and EPS approached a TD level, although statistical significance was not demonstrated.

Lastly, for patients with the highest GDI levels at E1, while the changes in gait were significant, seven patients (Good_to_Poor) experienced a reduction in GDI (increase in GPS), indicating an unsuccessful surgical outcome. They exhibited a decrease in EDI

from 83.73 at E1 to 82.11 at E2, with their DMC being significantly lower than that of Good_to_Good at E1 (78.08 vs. 82.68, p -value = 0.041). Good responders also had a higher initial level of DMC compared to mild responders (78.95 vs. 82.68, p -value = 0.038). Further, the changes in EMG for good responders from E1 to E2 were significant, as measured by EDI (p -value = 0.044) and EPS (p -value = 0.035).

Table 8 also shows the details of the main distal and proximal surgeries for the responders in this study. Dividing the total number of surgeries by the total number of patients for each condition, the average number of surgeries each patient underwent was calculated. To have clinical meaning, we have rounded this number. The better responders with a poor gait (Poor_to_Good) underwent more surgeries (on average 4) than the others (on average 3 and 2). In general, the number of proximal surgeries was relatively higher than distal surgeries for the patients with a better post-operative gait (21 vs. 15 for Poor_to_Good and 25 vs. 23 for Mild_to_Good).

Table 8. Comparison between the type and number of surgeries for each responding condition. Achilles tendon lengthening (ATL), Baumann procedure (BP), Strayer procedure (SP), bony foot procedures (BFP), femoral derotation (FD), rectus transfer (RT), hamstring lengthening (HL).

Responders	Total Number of Patients	Distal Surgeries				Proximal Surgeries			Average Number of Surgeries on One Patient	Total Number of Distal Surgeries	Total Number of Proximal Surgeries
		ATL	BP	SP	BFP	FD	RT	HL			
Poor_to_Good	10	1	6	5	3	10	7	4	4	15	21
Poor_to_Mild	22	6	10	9	3	21	11	14	3	28	46
Poor_to_Poor	11	0	3	7	4	9	4	1	3	14	14
Mild_to_Good	15	3	8	8	4	13	6	6	3	23	25
Mild_to_Mild	21	2	12	9	9	20	7	9	3	32	36
Mild_to_Poor	21	6	7	12	11	17	3	6	3	36	26
Good_to_Good	30	5	16	11	11	20	5	3	2	43	28
Good_to_Mild	30	5	10	14	16	16	5	3	2	45	24
Good_to_Poor	7	1	4	2	3	4	2	1	2	10	7

4. Discussion

This study confirms the systematic changes in EMG observed in patients with cerebral palsy following orthopedic surgery. In a relatively larger and more homogeneous cohort, we observed the same findings as Patikas et al. [5] regarding the improvement in post-operative norm-distance for kinetics, kinematics, and EMG (Tables 2 and 3).

The post-operative reduction in soleus activity during initial contact and terminal swing (Figure 2A) may be attributed to the decreased equinus following the (gastrocnemius) lengthening procedures. This adjustment, common in our population, allowed for a more dorsiflexed position during initial contact. Additionally, the increased activation of the soleus during terminal stance can enhance power generation in the plantar flexors, which is crucial for the body's forward progression [29].

Moreover, while increased mid-swing EMG activity of the rectus femoris is typically observed in individuals with cerebral palsy [30], the reduction in this activity post-surgery indicates a positive effect on their gait (Figure 2B). The increase in rectus femoris activity during early stance can also provide sufficient moment to extend the knee in mid-stance. During gait, as the knee extends and the ankle dorsiflexes, the knee moment transitions from an extensor to a flexor moment, allowing the quadriceps to cease contracting and the ankle to absorb power through the eccentric contraction of the gastrocnemius–soleus complex [31]. These synergistic changes observed in our study in the EMG of the soleus and rectus muscles may result in an improved plantar flexion–knee extension coupling mechanism [31], leading to better gait quality as indicated by the GDI and GPS (Table 2).

In addition to the soleus, Patikas et al. [5] reported a systematic improvement in the EMG activity of the lateral gastrocnemius, tibialis anterior, and medial hamstring in their

study, while the changes observed in the rectus femoris were not significant. Additionally, it has been demonstrated that the activation timing of the semitendinosus and vastus lateralis muscles changes following hamstring lengthening procedures [7]. These changes have been attributed not only to biomechanical modifications but also to altered recruitment of muscles that were not directly treated surgically. This suggests that different multilevel surgical procedures can influence the activation of various muscle groups.

In the present study, strict inclusion criteria were applied to ensure a more homogeneous surgical approach, focusing on patients who underwent soft tissue surgeries on muscles located at the shank and foot level, among other procedures. The observed differences between our results and those in the literature may stem from this restrictive inclusion criterion, which distinguishes our population from other studies. We propose that the improvement in the plantar flexion–knee extension coupling mechanism, driven by better activation patterns in the soleus and rectus femoris, is likely the primary contributor to the observed improvements in gait post-surgery for this population. It appears that other muscles, such as the tibialis anterior, gastrocnemius, and hamstrings, did not significantly contribute to this improvement.

The examined EMG indices, EDI and EPS, basically describe EMG patterns and show a tendency to approach typically developed (TD) levels, as indicated by a reduction in ND (Table 3), corresponding to improvements in gait following surgery (gait parameters, Table 2). This might be interpreted as a biomechanical aspect of EMG activity. In contrast, DMC seems to be a quantity that is relatively independent of the changes in gait patterns or indexes derived from them (Table 3). Therefore, and this is the second hypothesis we examined in this study, DMC can be a partial predictor of outcomes: ‘Good DMC = good response; Poor DMC = poor response’ (i.e., of orthopedic/biomechanical intervention). According to [21], we applied a clustering algorithm to divide the subjects into groups of patients with similar gait quality in E1 and the same response to the treatment in E2.

Considering the possible recovery conditions, DMC was the only measure that showed a difference between the responding groups with the same baseline GDI (Tables 5–7), while it remained the same from E1 to E2. The patients with a relatively low DMC (≈ 70 out of 100 for TD) along with poor gait quality ($GDI \approx 40$ out of 100 for TD) are more likely to have worse outcomes after treatment (Table 5). This finding interestingly implies that orthopedic surgeons should be cautious not to overtreat patients with severely limited motor control. Conversely, a relatively high DMC (≈ 80 out of 100 for TD) for patients with a better pre-treatment GDI (≈ 70 out of 100 for TD) can lead to further improvement in their gait following the intervention (Table 7). Moreover, for mild cases (Table 6), it can also be seen that the average DMC for the good responders was higher than for the other groups. However, for these cases, it might be difficult to distinguish between the biomechanics and the motor effect on their gait deficit.

It should be noted that DMC was the only measure in our study that significantly differentiated between responders, particularly in two groups: (1) poor responders with worse pre-treatment gait quality and (2) good responders with relatively high baseline GDI. While the averages presented in Tables 5–7 demonstrate that DMC differs between responders and has the potential as a predictor in clinical decision-making, our final conclusions are statistically valid only for these two specific responder groups.

It is crucial to acknowledge that the descriptive terms used in this study, such as poor, good, mild, better, and worse, are context-specific and pertain to the population included in our research. In other clinical settings, where the severity levels of patients may differ, these thresholds might not apply uniformly. Nevertheless, the inclusion of 167 patients in our study provides a sufficiently large sample size to generalize the systematic changes in EMG post-surgery, validate the application of EMG indices in clinical practice, and underscore

the significance of DMC as a measure of motor control function in clinical decision-making. While prior studies addressed pre-treatment femoral anteversion [32], knee flexion [33], dynamic hip flexion [34], and gait profile score [35] as predictors of postoperative outcomes, this is the first study to examine the connection between DMC and gait following surgery in a relatively homogeneous group of patients with CP.

Comparing the type and number of surgeries among the responders, it appears that those with poor pre-treatment gait quality who demonstrated better responses underwent the most extensive surgical interventions. Furthermore, proximal surgeries, such as rectus transfer, hamstring lengthening, and femoral derotation, seem to have resulted in higher responder rates compared to distal surgeries, such as Baumann–Strayer and bony foot procedures, for patients with initially poor and mild gait quality. However, in other responding groups, such as patients with good pre-treatment gait quality, distal surgeries are more prevalent than proximal ones. Although the variability in the type and number of surgeries introduces a potential source of bias in the grouping methodology used in this study, adjusting for this variable lies beyond the scope of this research.

It is important to emphasize that treatment for patients with CP typically begins in early childhood and continues throughout their lifetime. Moreover, patients often undergo multiple corrective procedures targeting both soft tissue and bone deformities within a single orthopedic intervention, commonly referred to as single-event multi-level surgery (SEMLS). These surgeries are often performed by different surgeons at various stages of treatment, introducing additional variability to the therapeutic process. Consequently, when working with large datasets, it becomes clinically challenging to disentangle the effects of factors such as the type and number of treatments, the expertise of the surgeon or clinician, and other contextual variables.

Our research primarily focused on the applicability of EMG as a clinical measure to enhance decision-making for patients with CP. However, we recommend that future researchers conduct more focused studies on the impact of different surgical approaches on EMG changes and their relationship with gait improvement. Additionally, the influence of growth, changes in muscle mass, and spasticity over time, particularly following surgery, on the EMG and gait of patients with cerebral palsy should also be explored in future studies.

One of the factors that may influence the results is the patients' growth, including both changes in body mass and height. While it is well-established that the gait patterns of typically developing children over the age of 8 closely resemble those of adults [36], this relationship is not sufficiently confirmed in children with CP, especially in longitudinal studies. The ability of the neuromuscular system in children with CP to adapt to growth and anatomical changes remains unclear. For example, increases in body weight in the presence of structural abnormalities may necessitate changes in muscle activation, such as recruitment or inhibition of muscles that typically do not alter their activation patterns with maturation. Additionally, spasticity levels, which can vary significantly across the cohort, may also have a significant impact on muscle activation patterns and gait. These factors, particularly the effects of aging, spasticity, and growth, could introduce variability in the data, and while we have noted their potential influence, they were not the primary focus of this study. This limitation may warrant further exploration in future research to better understand their role in surgical outcomes for children with CP.

From a clinical perspective, this study highlights the importance of integrating DMC and EMG indices into pre-surgical evaluations to enhance the prediction of surgical outcomes in patients with CP. For individuals with poor gait quality ($GDI \approx 40/100$) and low motor control ($DMC \approx 70/100$), the findings suggest that incorporating motor control interventions prior to surgery may improve outcomes. Conversely, patients with better pre-treatment gait quality ($GDI \approx 70/100$) and higher DMC scores ($\approx 80/100$) are more

likely to benefit from surgery. These insights provide a framework for tailoring treatment plans and optimizing clinical decision-making.

Author Contributions: M.D.: writing original draft, data analysis; F.S.: review and editing, methodology; R.R.: data analysis; D.A.P., N.A.B. and K.S.G.: review and editing; S.I.W.: review and editing, conceptualization, methodology, project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the German Research Foundation (DFG) (no: WO 1624/8-1). This funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics “Committee of the Medical Faculty, Heidelberg University Hospital” with the serial number S-243/2022 and approval date: 11 April 2022.

Informed Consent Statement: The data analyzed in this retrospective study were part of a larger database established at the local University Clinics in the years 2000–2022 when retrieval was stopped. Only personnel who had regular legal access to the medical records retrieved patient data. They collected data in the time of November and December 2022 and anonymized it in the same year, 28 December. After this step, individual participants could not be identified anymore. This study was approved by the local Ethical Committee (no: S-243/2022), waiving the requirement for informed consent.

Data Availability Statement: The data supporting the conclusions of this article will be made available by the authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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