# Predicting Rehabilitative Prognosis of Spinal Fusion Surgery in Cerebral Palsy Patients with Cervical Myelopathy

**Jihye Hwang**

**Graduate Program of Biomedical Engineering**

**The Graduate School, Yonsei University**

# Predicting Rehabilitative Prognosis of Spinal Fusion Surgery in Cerebral Palsy Patients with Cervical Myelopathy

**Directed by Professor Sung-Rae Cho**

**Master's Thesis**

**submitted to the Graduate Program of Biomedical Engineering,**

**in the Graduate School of Yonsei University**

**in partial fulfillment of the requirements for the degree of**

**Master of Biomedical Engineering**

**Jihye Hwang**

**December 2024**

**This certifies that the Master's thesis**

**of Jihye Hwang is approved.**

**Thesis Supervisor: Dr. Sung-Rae Cho, M.D, Ph.D**

**Dr. Yoon Ha, M.D, Ph.D: Thesis Committee Member #1**

**Dr. Hyeon Chang Kim, M.D, Ph.D: Thesis Committee Member #2**

The Graduate School

Yonsei University

December 2024

# ACKNOWLEDGEMENT

I would like to extend my heartfelt gratitude to my professor, Dr. Sung-Rae Cho, whose unwavering support and boundless generosity have been invaluable throughout the journey for the attainment of my Master's degree. From beginning till the end, insights and stimulating discussions in the domain of clinical rehabilitation have been instrumental in shaping the intellectual rigor and depth of this thesis.

Particularly indebted to his extraordinary patience and understanding, I am honored have studied under Dr. Cho's distinguished tutelage as I carry forward the knowledge and inspiration imparted in me as I progress in my career. In addition to his discerning guidance and meticulous attention to detail that have refined my academic abilities and cultivated my capacity for critical inquiry, the completion of this thesis itself holds a significance in evidence of trust and autonomy he afforded me in conducting my research.

I would also like to extend my sincere appreciation to Professor Yoon Ha and Professor Hyeon Chang Kim for their invaluable contributions to the completion of this thesis. Professor Yoon Ha offered insightful feedback on the neurosurgical aspects of my research, enriching my understanding of the

complexities involved in the field. His expertise in neurosurgery and thoughtful suggestions were pivotal in ensuring the clinical relevance of my work. I am equally grateful to Professor Hyeon Chang Kim, for his critical support in clinical statistics. His guidance in refining the analytical approach and ensuring the accuracy of my data interpretation has been indispensable in strengthening the scientific integrity of my thesis.

In reflection, the collective mentorship I have received from these distinguished scholars has profoundly impacted both my academic trajectory and professional aspirations.

# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF FIGURES

**ABSTRACT**

Cerebral palsy (CP), a heterogeneous neurodevelopmental disorder characterized by motor dysfunction, poses unique challenges when compounded by cervical myelopathy, a condition arising from chronic spinal cord compression. Cervical myelopathy often progresses undiagnosed in CP patients due to overlapping symptoms, resulting in severe motor and sensory impairments. This study aims to evaluate the combined predictive value of spinal cord compression ratio, duration of symptoms, and CP subtype on postoperative functional outcomes in CP patients undergoing spinal fusion surgery. Functional outcomes were assessed using the Modified Barthel Index (MBI), a measure of independence in activities of daily living. The study hypothesized that higher spinal cord compression ratio would positively correlate with improved MBI scores, while prolonged duration of symptoms and the dyskinetic CP subtype would negatively impact recovery. Findings confirmed spinal cord compression ratio as a significant independent predictor, with higher values associated with better postoperative

function due to reduced spinal cord compression. Conversely, prolonged duration of symptoms led to irreversible neuronal damage, emphasizing the critical importance of timely surgical intervention. Dyskinetic CP emerged as a poor prognostic factor due to abnormal sensorimotor integration and uncontrolled movement in the cervical region, which undermines surgical stability and necessitates more intensive rehabilitation. Results from this study highlight the need for early diagnosis and intervention in CP patients with cervical myelopathy to optimize surgical outcomes and prevent long-term disabilities. Spinal cord compression ratio and duration of symptoms, alongside CP subtypes, serve as critical tools for preoperative counseling and postoperative planning. This study thus emphasizes the importance of a holistic approach to spinal fusion surgery in CP patients, emphasizing the interplay of radiological, clinical, and demographic factors in predicting recovery.

*Keywords: cerebral palsy, cervical myelopathy, spinal cord compression ratio, dyskinetic, duration of symptoms*

# I. INTRODUCTION

## 1. Background

Cerebral palsy (CP) is a chronic neurodevelopmental condition incurred by non-progressive brain injury during prenatal, perinatal and postnatal stages of development [1]. With average global frequency of CP being 1.6 to 3.4 children per 1000 born and 2 to 2.5 children per 1000 born in the United States, CP continues to affect the lives of many people regardless of the level of development of the region they live in [2, 3]. Prenatal complications like intrauterine infections, perinatal complications including hypoxic-ischemic encephalopathy, preterm birth, and birth asphyxia, alongside postnatal causes such as neonatal infections, traumatic brain injuries, or severe jaundice leading to kernicterus are key contributing causes of the multifactorial etiology of CP [4]. As a heterogeneous group of clinical syndromes characterized by motor dysfunctions that affect movement, posture, and coordination, diagnosis of CP is mostly made clinically facilitated by radiological

findings in the brain [5]. Previous publications report brain abnormalities in 86% of radiological imaging, with white matter injury being the most common (19 – 45%) followed by other patterns including grey matter injury (21%) and focal vascular insults (10%) [6].

Pathological cerebral lesion in the developing brain — depending on its type, location and degree — results in abnormal motor functions and even cognitive decline that degrades quality of life [7]. In children, periventricular white matter lesions are known to result in better hand function compared to focal ischemic infarcts and basal ganglia and thalamus involvement [7]. A unilateral brain lesion may sometimes disrupt the growth of contralateral pathways, contributing to the persistence of ipsilateral projections and thus less effective motor control [7].

Among the various subtypes, spastic CP accounts for approximately 80% of cases [8]. Spastic CP can be topographically classified into quadriplegia, diplegia and hemiplegia based on the

involvement of the limbs in spastic type [9]. Evidence shows a diplegic pattern of is associated with birth shorter than at 32 weeks [9]. Dyskinetic and ataxic types are not topographically classified[8]. The spastic subtype is marked by increased muscle tone, hyperreflexia, and muscle stiffness, which impair voluntary movement and lead to gait abnormalities, such as stiff-knee in swing, scissoring or toe-walking [10, 11]. These motor impairments often lead to secondary complications over time, including joint deformities, and muscle contractures, further exacerbating functional limitations and reducing independence [10].

One of the most severe complications in older CP patients is cervical myelopathy, a pathologic condition arising from chronic spinal cord compression, particularly in the cervical spine [12]. Cervical myelopathy is often a result of static pathophysiological changes such as cervical spondylosis, cervical radiculopathy, kyphotic deformities, or ossification of the posterior longitudinal ligament and ligamentum flavum, which are more prevalent in CP patients due to abnormal biomechanical stress on the spine [13, 14]. Dynamic factors like neck

flexion and extension movements may also narrow the cervical spinal canal and therefore contribute to the strain and shear forces on the spinal cord. Some studies also report on the critical role of biomolecular forces including ischemic injury from chronic vascular compression and glutamate-mediated excitotoxicity in triggering abnormal development of cervical myelopathy [14, 15]. Persistent spasticity, abnormal postural alignment, and repetitive strain on the cervical vertebrae may accelerate degenerative changes, leading to progressive narrowing of the spinal canal and eventually intramedullary hypertrophy in the cervical region if left untreated for a prolong period [14, 16, 17].

Cervical myelopathy presents with a range of neurological symptoms, including limb weakness, gait disturbances, and spasticity, which may exacerbate pre-existing motor deficits from CP. Signs from neurological manifestations often include subtle changes in dexterity, such as difficulty with fine motor tasks, and nonspecific sensory disturbances like stiffness, prickling pain, radiating pain, numbness or tingling in the neck, trapezius, anterior chest, shoulder, lateral arm,

forearm and hands, depending on the level of vertebrae affected [13]. As the condition progresses, patients may develop more pronounced motor dysfunction, including increased difficulty walking, frequent falls, and spastic paraparesis or quadriparesis. Advanced cases of cervical myelopathy in CP patients can also exhibit bowel and bladder dysfunction due to impaired autonomic control, as cervical myelopathy may further progresses to the adjacent regions of spinal cord and continue to disturb the corticospinal tract [18]. Early recognition and appropriate management are therefore critical to preserving function and preventing long-term complications in this vulnerable population.

Cervical myelopathy in CP patients is often underdiagnosed due to overlapping symptoms with their baseline motor deficits. Hence, when left untreated, it progresses to severe motor impairment, sensory disturbances, and loss of independence in daily activities. Surgical intervention, specifically spinal fusion surgery, is a widely adopted treatment for cervical myelopathy [19]. This procedure is aimed at stabilizing the spine, alleviating compression on the spinal cord, and

correcting the alignment to improve neurological function [19]. Despite the procedural advancements, postoperative outcomes in CP patients remain unpredictable depending on the number of motion segments involved, warranting further investigation into factors that influence recovery [19].

Three key factors that garnered recognition in predicting surgical outcomes are the spinal cord compression ratio, duration of symptoms and the type of CP. Spinal cord compression ratio, a radiological parameter quantifying the degree of spinal cord compression, serves as a critical determinant of the severity of cervical myelopathy [20-22]. A higher spinal cord compression ratio indicates less compression and generally demonstrates a better prognosis post-surgery.

Duration of symptoms reflects the time elapsed between the day first symptom onset was reported and the day of first spinal fusion surgical intervention. Conversely, prolonged duration of symptoms, often from reluctance of patients in undertaking an invasive treatment

like the surgery and delayed diagnosis of cervical myelopathy, is only expected to result in irreversible neuronal damage especially if cervical myelopathy already manifests as symptomatic [16, 23, 24].

Patients with dyskinetic type of CP experiences abnormal sensorimotor integration, implying that the brain processes and reacts to sensory inputs incorrectly [25, 26]. This abnormal plasticity makes the condition resistant to immediate therapeutic intervention as it consolidates these dysfunctional patterns as poor motor memories [25]. Once these abnormal motor patterns become firmly established, traditional interventions like spinal fusion surgery may no longer have positive outlook [26]. While these factors have been individually studied in general populations with cervical myelopathy, their combined predictive value in the context of CP remains underexplored.

## 2. Necessity of Study

CP patients represent a unique demographic with distinct anatomical

and functional challenges and are particularly vulnerable to the natural process of age related neurodegenerative complications such as cervical myelopathy. Should cervical myelopathy progress to become symptomatic, their predisposition to spinal deformities and altered biomechanics necessitates immediate tailored clinical attention. However, current literature on cervical myelopathy predominantly focuses on the general adult population, with limited application to CP patients[27, 28]. This disparity poses significant challenges for clinicians in devising effective treatment plans for this vulnerable group.

The limited understanding of how spinal cord compression ratio and duration of symptoms interact to influence functional outcomes post-surgery in CP patients highlights a critical gap in knowledge. Addressing this gap is essential for several reasons. First, identifying the role of these factors can optimize the timing of surgical interventions, potentially preventing irreversible damage where the neurologic integrity of spinal cord had been breached. Second, elucidating the quantitative contributing power of spinal cord

compression ratio, duration of symptoms and CP subtypes could serve as a valuable tool for preoperative counseling and postoperative rehabilitation planning. Lastly, insights gained from this study could guide better resource allocation for stakeholders such as clinicians in the field and government bodies, ensuring that high-risk patients receive comprehensive and timely care.

### 3. Purpose of Study

The primary objective of this study is to evaluate the combined contributive value of spinal cord compression ratio, duration of symptoms and type of CP on functional outcomes in CP patients with cervical myelopathy undergoing their first anterior and/or posterior spinal fusion surgery. Functional outcome from rehabilitative perspective will be assessed using the Modified Barthel Index (MBI), a widely recognized measure of independence in activities of daily living. The study therefore aims to determine whether spinal cord compression

ratio, duration of symptoms and type of CP are significant contributors of postoperative MBI scores.

## 4. Hypothesis

It is hypothesized that spinal cord compression ratio will have a positive association with postoperative MBI scores, with higher values indicating better recovery. In contrast, it is expected that duration of symptoms will negatively correlate with MBI scores, with longer symptom durations predicting worse outcomes. Dyskinetic CP subtype is also expected to have a negative prognosis due to the consistent yet uncontrolled movement in the cervical region post-surgery. The combined analysis of these variables is anticipated to yield an evidence-based recommendation for apt surgical timing and rehabilitation strategies.

## II. MATERIALS AND METHODS

### 1. Patient Selection and Study Design

This retrospective single center cohort study from March 2006 to May 2024 included 75 patients diagnosed with CP and cervical myelopathy who underwent anterior and/or posterior spinal fusion surgery with cage or plate under the Department of Neurosurgery and admitted to the Department of Rehabilitation Medicine for post-surgical observation at Severance Hospital, Seoul, Republic of Korea (Table 1). Inclusion criteria is as follows: (1) confirmed clinical diagnosis of cerebral palsy, irrespective of subtype (2) clinical and radiographic confirmation of cervical myelopathy by a specialized radiologist with visible spinal cord compression of the cervical region on magnetic resonance imaging (3) aged at least 18 years or older at the time of surgical intervention (4) ability to understand the study and provide informed consent (or via legal guardian for patients with cognitive impairments). Exclusion criteria included: (1) presence of any other major medical conditions such as advanced heart disease, severe respiratory conditions or

terminal illnesses like cancer (2) patients with progressive neurological diseases other than CP that could confound the analysis of rehabilitation outcomes, such as amyotrophic lateral sclerosis, multiple sclerosis, autoimmune disease for peripheral neuropathy (3) patients with contraindications for undergoing spinal fusion surgery, such as uncontrolled bleeding disorders or other risk factors for surgical complications (4) pregnant women (5) patients with medical records that were barely recognizable (such as MRI) (6) those with largely missing medical data or had been lost to follow up over a period of at least 1 year.

**Table 1. Patient baseline characteristics.**

| Patient No. | Sex | Age (Years) | Duration of symptoms (months) | BMD | Type of CP | Spinal cord compression ratio | Hypertrophy |
|---|---|---|---|---|---|---|---|
| 1 | Female | 47 | 85.0 | Normal | Dyskinetic | 0.524 | Present |
| 2 | Female | 45 | 42.0 | Osteoporosis | Spastic | 0.734 | Present |
| 3 | Male | 44 | 137.1 | Osteoporosis | Dyskinetic | 0.899 | Present |
| 4 | Male | 35 | 61.1 | Normal | Spastic | 0.732 | Present |
| 5 | Male | 52 | 1.0 | Normal | Spastic | 0.701 | Present |
| 6 | Male | 38 | 109.2 | Osteopenia | Dyskinetic | 0.530 | Present |
| 7 | Male | 36 | 62.8 | Osteopenia | Dyskinetic | N/A | Absent |
| 8 | Male | 41 | 37.1 | Normal | Dyskinetic | 0.675 | Absent |
| 9 | Female | 40 | 64.4 | Normal | Dyskinetic | 0.415 | Present |
| 10 | Male | 58 | 122.5 | Normal | Spastic | 0.549 | Present |
| 11 | Male | 47 | 28.3 | Osteoporosis | Spastic | 0.590 | Absent |
| 12 | Female | 36 | 1.6 | Osteopenia | Dyskinetic | 0.454 | Absent |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 13 | Male | 30 | 16.3 | Normal | Spastic | 0.586 | Present |
| 14 | Male | 47 | 85.2 | Normal | Spastic | 0.616 | Present |
| 15 | Female | 32 | 7.6 | Osteopenia | Spastic | 0.304 | Present |
| 16 | Female | 41 | 7.1 | Osteopenia | Dyskinetic | 0.432 | Present |
| 17 | Male | 33 | 2.9 | Normal | Spastic | 0.530 | Present |
| 18 | Male | 25 | 61.3 | Normal | Dyskinetic | 0.733 | Present |
| 19 | Male | 43 | 170.0 | Normal | Spastic | 0.306 | Present |
| 20 | Male | 42 | 36.5 | Osteoporosis | Spastic | 0.760 | Present |
| 21 | Male | 25 | 3.1 | Normal | Spastic | 0.716 | Present |
| 22 | Male | 40 | 60.9 | Normal | Dyskinetic | 0.714 | Present |
| 23 | Male | 44 | 97.4 | Osteopenia | Dyskinetic | N/A | Absent |
| 24 | Female | 38 | 24.2 | Osteopenia | Spastic | 0.498 | Present |
| 25 | Male | 50 | 12.4 | Osteoporosis | Spastic | 0.731 | Present |
| 26 | Male | 46 | 170.1 | Osteopenia | Spastic | 0.408 | Present |
| 27 | Male | 49 | 30.6 | Osteopenia | Dyskinetic | 0.613 | Present |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 28 | Female | 41 | 76.8 | Osteopenia | Spastic | 0.712 | Present |
| 29 | Male | 36 | 3.1 | Osteoporosis | Dyskinetic | 0.744 | Present |
| 30 | Male | 25 | 1.4 | Normal | Spastic | 0.540 | Present |
| 31 | Male | 38 | 67.1 | Osteoporosis | Dyskinetic | 0.641 | Present |
| 32 | Female | 40 | 170.6 | Osteoporosis | Spastic | 0.350 | Present |
| 33 | Female | 51 | 88.2 | Osteoporosis | Dyskinetic | 0.748 | Present |
| 34 | Male | 47 | 13.4 | Normal | Spastic | 0.486 | Present |
| 35 | Male | 37 | 3.0 | Normal | Spastic | 0.794 | Absent |
| 36 | Male | 36 | 1.5 | Normal | Dyskinetic | 0.479 | Present |
| 37 | Male | 18 | 250.1 | Osteopenia | Spastic | 0.520 | Present |
| 38 | Female | 35 | 6.2 | Osteopenia | Spastic | 0.484 | Present |
| 39 | Male | 72 | 219.2 | Osteoporosis | Dyskinetic | 0.605 | Present |
| 40 | Female | 30 | 3.0 | Osteoporosis | Spastic | 0.534 | Present |
| 41 | Male | 39 | 24.4 | Osteoporosis | Spastic | 0.510 | Present |
| 42 | Female | 47 | 132.3 | Normal | Spastic | 0.636 | Absent |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 43 | Female | 39 | 82.5 | Normal | Spastic | 0.496 | Present |
| 44 | Male | 53 | 5.9 | Osteoporosis | Spastic | 0.484 | Present |
| 45 | Female | 48 | 8.8 | Osteopenia | Spastic | 0.673 | Present |
| 46 | Female | 62 | 36.5 | Osteoporosis | Dyskinetic | 0.426 | Present |
| 47 | Female | 33 | 4.5 | Normal | Dyskinetic | 0.703 | Present |
| 48 | Female | 39 | 17.3 | Normal | Spastic | 0.512 | Present |
| 49 | Female | 45 | 19.5 | Normal | Spastic | 0.793 | Present |
| 50 | Male | 56 | 1.9 | Normal | Spastic | 0.311 | Present |
| 51 | Female | 41 | 12.2 | Osteoporosis | Spastic | 0.584 | Present |
| 52 | Female | 58 | 74.3 | Osteopenia | Spastic | 0.823 | Present |
| 53 | Female | 45 | 94.6 | Normal | Dyskinetic | 0.680 | Present |
| 54 | Male | 38 | 3.1 | Osteoporosis | Spastic | 0.594 | Present |
| 55 | Male | 31 | 6.9 | Osteoporosis | Spastic | 0.448 | Present |
| 56 | Male | 45 | 6.2 | Normal | Dyskinetic | 0.627 | Present |
| 57 | Female | 42 | 59.8 | Normal | Spastic | 0.748 | Present |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58 | Male | 69 | 13.1 | Osteopenia | Dyskinetic | 0.814 | Present |
| 59 | Male | 56 | 676.5 | Osteoporosis | Spastic | 0.272 | Present |
| 60 | Male | 50 | 66.7 | Osteopenia | Dyskinetic | 0.366 | Present |
| 61 | Female | 44 | 410.3 | Osteopenia | Spastic | 0.618 | Present |
| 62 | Female | 42 | 510.3 | Normal | Spastic | 0.498 | Present |
| 63 | Male | 47 | 341.0 | Normal | Dyskinetic | 0.682 | Present |
| 64 | Female | 50 | 375.9 | Normal | Spastic | 0.549 | Present |
| 65 | Male | 56 | 678.5 | Osteopenia | Dyskinetic | 0.334 | Present |
| 66 | Male | 38 | 45.4 | Osteopenia | Dyskinetic | 0.751 | Present |
| 67 | Female | 48 | 36.5 | Osteopenia | Spastic | 0.628 | Present |
| 68 | Female | 39 | 18.7 | Normal | Dyskinetic | 0.356 | Present |
| 69 | Female | 62 | 130.0 | Normal | Spastic | 0.594 | Present |
| 70 | Female | 51 | 80.7 | Osteopenia | Spastic | 0.419 | Present |
| 71 | Female | 52 | 48.3 | Normal | Spastic | 0.417 | Present |
| 72 | Male | 48 | 24.3 | Normal | Spastic | 0.736 | Absent |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 73 | Male | 38 | 2.0 | Osteoporosis | Spastic | 0.766 | Present |
| 74 | Male | 49 | 141.0 | Normal | Dyskinetic | 0.832 | Present |
| 75 | Male | 45 | 245.3 | Normal | Spastic | 0.605 | Present |

***Note. The table presents individual patient data, including demographic and clinical characteristics. Sex is listed as male or female. Age is in years. Duration of Symptoms is reported in months. Bone Mineral Density (BMD) is categorized as normal, osteopenia, or osteoporosis. Type of CP refers to the classification of cerebral palsy (spastic or dyskinetic). Spinal Cord Compression Ratio is presented as a numeric value where available. Hypertrophy refers to the presence or absence of spinal hypertrophy. Missing data are marked as N/A.***

***Abbreviations. BMD: Bone Mineral Density; MBI: Modified Barthel Index; N/A, Not Available.***

## 2. Data Collection

All patient data has been collected from the Electronic Medical Records, Severance Hospital, Seoul, Republic of Korea. Data collection focused on demographic information, clinical history, and preoperative assessments. Patients' ages at the time of surgery, range of cervical myelopathy, presence of hypertrophy, bone mineral density (normal, osteopenia and osteoporosis) based on the T-score of their bone mineral density evaluation of the lumbar region, and their sex were documented.

Duration of symptoms, defined as the time elapsed between the Reported onset of neurological symptoms, such as limb weakness or gait instability and surgical intervention, was recorded in months. The Modified Ashworth Scale was used to assess spasticity and thus classify CP subtypes. Scores ranged from zero, representing no increase in muscle tone, to four, indicative of rigid limb spasticity. Patients with a minimum score of 1 were classified into spastic and others into dyskinetic if they did not show any signs of velocity-dependent increase

in muscle tone when their upper and lower limb muscles were passively stretched by trained physical therapists during the pre-assessment.

Detailed reviews of preoperative, imaging studies, and rehabilitation progress notes were also taken. Measurements were performed at each cervical vertebra from C1 to C7, ensuring a perpendicular angle of 90 degrees to the spinal axis at the level of interest. Similarly, spinal cord compression ratio was calculated using preoperative MRI by determining the anterior-posterior ratio of the affected sagittal spinal cord diameter to the average sagittal spinal cord diameters from C1 to C7, and expressing this value as a rounded-up value to one decimal point in millimeters (Figure 1). The anterior-posterior diameter of the spinal cord was recorded for each vertebra. The smallest AP diameter among the measured levels was identified as the numerator, representing the most severe point of spinal cord compression. MRI images were analyzed using a Picture Archiving and Communication System (ZeTTA PACS; TaeYoung Soft Co., Ltd., Version 2.0.3.5.2.1.; 2023). Functional independence in activities of

daily living was evaluated preoperatively using MBI. MBI assessments were conducted by physical therapists three months and 12 months following surgery, with patients categorized into deterioration outcome group with any numerical decrease in score and into preserved outcome group with any increase or maintenance in score numerically (Table 2).

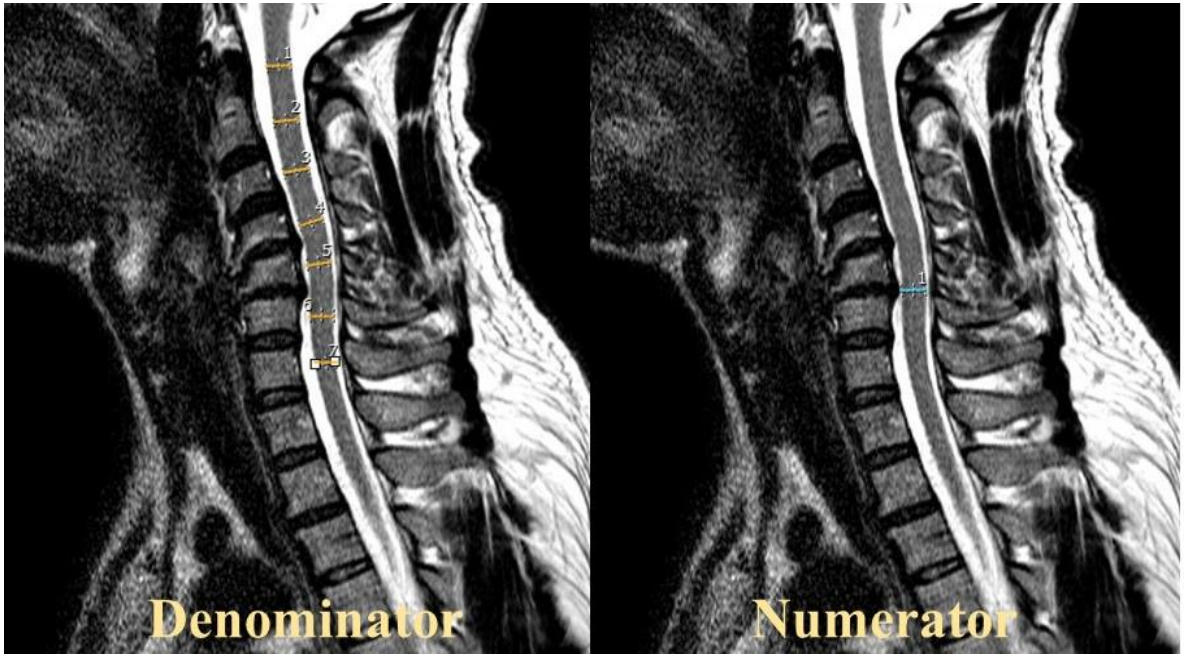


**Figure 1. T2-MRI (sagittal view) indicating AP diameters of the cervical spinal cord marked by dotted lines numbered from 1 to 7 (left) as denominator and marked by a dotted line as 1 (right).**

### 3. Surgical Procedures

All patients underwent spinal fusion surgery, performed using either an anterior or posterior approach, depending on the anatomical and pathological features of their condition [29]. The choice of approach was tailored to each patient following detailed preoperative evaluations, including MRI and CT imaging, to determine the degree of spinal cord compression, spinal alignment, and any associated deformities [29]. Neurological examinations and functional assessments further guided the surgical planning process [29]. All surgery has been performed by well-experienced neurosurgeons.

### 4. Rehabilitation Protocol

Postoperative rehabilitation was initiated after 48 hours of surgery with ample bed-rest in the immediate phase after surgery, following a conventional protocol designed to maximize functional recovery. Rehabilitation was conducted by a multidisciplinary team consisting of

physical therapists, occupational therapists, and physicians specializing in rehabilitation medicine. Early mobilization was emphasized, with range-of-motion exercises introduced shortly after surgery to prevent stiffness and maintain joint mobility. As patients' conditions stabilized, they were encouraged to participate in assisted transfers and ambulation if possible. Pain management was actively taken into consideration upon patient's request. Physical therapy included strengthening exercises targeting both upper and lower extremities, with a focus on reducing spasticity and improving motor control. Occupational therapy addressed daily living activities such as dressing, grooming, and feeding, with adaptive devices provided to meet individual needs. All physical therapy was conducted by trained physical therapists. All occupational therapy was conducted by trained occupational therapists.

**5. Data Analysis**

Descriptive statistics were used to summarize baseline characteristics,

including mean and standard error mean for continuous variables including spinal cord compression ratio, duration of symptoms and frequencies for categorical variable type of CP (spastic vs dyskinetic). Correlation analyses were performed to examine relationships between spinal cord compression ratio, duration of symptoms, and MBI scores. Univariable and multiple linear regression models were constructed to evaluate the predictive contributions of spinal cord compression ratio, type of CP and duration of symptoms to postoperative functional outcomes

**6. Statistical Analysis**

Demographical and clinical characteristics between the preserved outcome and deteriorated outcome groups were analyzed using following statistical analysis. Continuous variables such as age, spinal cord compression ratio, and preoperative MBI scores were analyzed using independent t-tests, with statistical significance set at $p < 0.05$.

Duration of symptoms, measured in months, did not follow a normal distribution and thus was analyzed using the Mann-Whitney U test ($p < 0.05$). Categorical variables including sex, type of CP, BMD, and the presence of hypertrophy were evaluated using the Chi-square test, with significance set at $p < 0.05$ as well. Univariable linear regression was used to calculate the contributing power and model performance for each individual independent factors. Multivariable linear regression was used to calculate the integrated contributing factor of all independent variables. Multicollinearity, residual normality, and homoscedasticity, were also conducted to ensure model validity and are reflected with regression analysis. Model performance was assessed using $R^2$ values, with statistical significance set at $p < 0.05$. All analyses were performed using SPSS version 28.0 (IBM Corp., Armonk, NY).

## 6. Ethical Considerations

This study retrospectively analyzes clinical data obtained in the course

of treatment that has already ended, and the study is conducted through the analysis of medical records from the aforementioned hospital EMR, and does not pose detrimental risk to human subjects. It does not collect prospective information from the subjects for research purposes. In order to strictly maintain the confidentiality of the patient's personal information throughout the entire research process, including the collection and analysis of clinical data, the writing of the paper, and the publication of the paper, research-related documents is stored in a locked device, coded with identifying information, all data de-identified before analysis, and stored on a computer with limited access, so as not to infringe on the rights or welfare of the patient.

This study was conducted in accordance with the principles outlined in the Declaration of Helsinki and approved by the Severance Hospital Institutional Review Board No. 4-2024-0643.

## III. RESULTS

A total of 75 CP patients with cervical myelopathy were included in the study's analysis. The cohort was divided into two groups: preserved outcome (n = 32) and deteriorated outcome (n = 43). There was no statistically significant difference in age between the preserved outcome (44.25 ± 1.84 years) and deteriorated outcome groups (42.77 ± 1.42 years) (p = 0.518) (Table 2). Similarly, the groups did not differ significantly in sex distribution with 65.5% male in the preserved outcome group compared to 53.5% male in the deteriorated outcome group (p = 0.291) or type of CP (spastic: 56.3% in the preserved outcome group vs. 67.4% in the deteriorated outcome group) (dyskinetic: 43.8% in the preserved outcome group vs. 32.6% in the deteriorated outcome group) (p = 0.322) (Table 2). No significant differences were observed in spinal cord compression ratio (preserved outcome: 0.611 ± 0.03 mm; deteriorated outcome: 0.57 ± 0.23 mm; p = 0.193) or duration of symptoms (preserved outcome: 63.83 ± 12.01 months; deteriorated outcome: 112.42 ± 26.41 months; p = 0.672)

(Table 2). BMD distributions were nearly identical between groups, with no significant difference (p = 0.998). Hypertrophy was present in 87.5% of the preserved outcome group and 90.7% of the deteriorated outcome group, with no significant difference (p = 0.657) (Table 2). Preoperative MBI scores were significantly higher in the deteriorated outcome group (53.00 ± 5.64) compared to the preserved outcome group (69.70 ± 4.05) (p = 0.016) (Table 2). At three months postoperatively, short-term MBI scores were similar between the two groups with preserved outcome groups showing a slightly higher score, although no significant difference observed (54.83 ± 5.68 vs. 54.03 ± 4.52, p = 0.911) (Table 2). Similarly, at one year postoperation, the long-term MBI score was higher in the preserved outcome group compared to the deteriorated outcome group, although the difference was not statistically significant (62.00 ± 5.87 vs. 52.12 ± 5.42, p = 0.223) (Table 2).

With regards to MBI score differences over time, patients in the preserved outcome group exhibited a significant short-term

improvement (1.92 ± 2.08), whereas patients in the deteriorated outcome group showed a marked decline (-18.59 ± 3.29, $p < 0.001$) (Table 2). Likewise, the long-term MBI improvement in the preserved outcome group (5.54 ± 4.23) was significantly greater than the substantial decline observed in the deteriorated outcome group (-33.08 ± 5.53, $p < 0.001$) (Table 2).

**Table 2. Demographic characteristics of patients according to their groups measured with MBI differences.**

| Variables | Preserved outcome (n = 32) | Deteriorated Outcome (n = 43) | p |
|---|---|---|---|
| **Age (year)** | 44.25 ± 1.84 | 42.77 ± 1.42 | 0.518 |
| **Sex (n, %)** | | | 0.291 |
| **Male** | 21 (65.5%) | 23 (53.5%) | |
| **Female** | 11 (34.4%) | 20 (46.5%) | |
| **Type of CP (n, %)** | | | 0.322 |
| **Spastic** | 18 (56.3%) | 29 (67.4%) | |
| **Dyskinetic** | 14 (43.8%) | 14 (32.6%) | |
| **Spinal cord compression ratio** | 0.611 ± 0.03 | 0.57 ± 0.23 | 0.193 |
| **Duration of symptoms (months)** | 63.83 ± 12.01 | 112.42 ± 26.41 | 0.672 |
| **BMD (n, %)** | | | 0.998 |
| **Normal** | 15 (46.9%) | 20 (46.5%) | |
| **Osteopenia** | 9 (28.1%) | 12 (27.9%) | |

| | | | |
|---|---|---|---|
| **Osteoporosis** | 8 (25.0%) | 11 (25.6%) | |
| **Hypertrophy (n, %)** | | | 0.657 |
| **Present** | 28 (87.5%) | 39 (90.7%) | |
| **Absent** | 4 (12.5%) | 4 (9.3%) | |
| **Pre-OP MBI** | 53.00 ± 5.64 | 69.70 ± 4.05 | 0.016* |
| **Short Term MBI (3months)** | 54.83 ± 5.68 | 54.03 ± 4.52 | 0.911 |
| **Long-Term MBI (1 year)** | 62.00 ± 5.87 | 52.12 ± 5.42 | 0.223 |
| **Short-Term MBI Difference** | 1.92 ± 2.08 | -18.59 ± 3.29 | <0.001*** |
| **Long-Term MBI Difference** | 5.54 ± 4.23 | -33.08 ± 5.53 | <0.001*** |

***Note. Statistical analysis for age, spinal cord compression ratio, Pre-OP MBI, short-term MBI, long-term MBI, short-term MBI difference and long-term MBI difference were performed with independent t-test with $p < 0.05$. Statistical analysis for duration of symptoms was performed with Mann-Whitney test, $p < 0.05$. Statistical analysis for sex, Type of CP, BMD, presence of hypertrophy were measured with Chi-Square test, $p < 0.05$.***

### 1. Spinal cord compression ratio is a strong significant prognostic factor of post-surgical outcome.

Univariable regression analysis was first conducted to evaluate the relationship between the spinal cord compression ratio as an independent variable and MBI total score (Table 3). The affected diameter of the cervical spinal cord served as the numerator while the average AP diameters of the cervical spinal cord served as the denominator. For short-term MBI scores, spinal cord compression ratio demonstrated a significant positive association ($B$=47.16, standard error =15.43, $\beta$=0.38, $t$=3.057, $p$=0.003) (Table 3). The model explained approximately 14.3% of the variance in short-term MBI scores ($R^2$=0.14), with a Durbin-Watson (DW) value at 1.964, indicating no substantial autocorrelation in the residuals (Table 3). The regression model was statistically significant ($F$=9.346, $p$=0.003) (Table 3).

Long-term MBI scores, however, spinal cord compression ratio

did not show a significant association ($B$= -14.92, standard error = 20.43, $\beta$= -0.11, $t$= -0.730, $p$=0.469) (Table 3). The model explained only 1.1% of the variance ($R^2$=0.01), and DW value was 2.30, thus indicated no issues with autocorrelation (Table 3). The overall regression model was not statistically significant. These findings suggest that a higher spinal cord compression ratio, indicating a relatively less compressed spinal cord, correlates with better short-term functional outcomes and therefore is a meaningful predictor of short-term MBI scores but not long-term MBI scores in this cohort.

Multivariable linear regression analysis was conducted to evaluate the relationship between spinal cord compression ratio and short-term MBI total scores while controlling for other variables, including age, sex, duration of symptoms, and type of CP (Table 3). The overall regression model was statistically significant ($F$=10.437, $p$<0.001) and explained 28.3% of the variance in short-term MBI scores ($R^2$=0.28), and a DW value of 2.11, indicating no substantial

autocorrelation in the residuals (Table 3). Among the predictors, spinal cord compression ratio ($\beta$=0.38, $t$=3.228, $p$=0.002) and age ($\beta$= -0.38, $t$= -3.258, $p$=0.002) showed significant associations with short-term MBI scores (Table 5). A higher spinal cord compression ratio, indicating less spinal cord compression, was positively associated with better short-term functional outcomes while older age was negatively associated with short-term MBI scores.

Other variables, including sex ($\beta$=0.02, $t$=0.154, $p$=0.878), duration of symptoms ($\beta$= -0.104, $t$= -0.826, $p$=0.413), and type of CP ($\beta$=0.09, $t$=0.809, $p$=0.422), were not significant predictors. Tolerance and variance inflation factor (VIF) values for all predictors were within acceptable ranges, indicating no statistical issues with multicollinearity (Table 3).

The normal P-P plot of regression standardized residuals for the model examining spinal cord compression ratio as a predictor of short-term MBI scores (Figure 2) demonstrated that the residuals closely

followed the diagonal regression line, implying an approximate normality. This supports the validity of the regression model and confirms that the relationship between spinal cord compression ratio and short-term MBI scores meets the assumption of normality for residuals, ensuring reliable statistical inferences. Spinal cord compression ratio is therefore a strong significant predictor of short-term MBI scores, alongside age, underscoring the relevance of these factors in early functional recovery of CP patients who underwent spinal fusion surgery of the cervical region.

A greater proportion of patients in the deteriorated outcome group exhibits a wider distribution along the lower spinal cord compression ratio axis in the short term (Figure 3). In contrast, the preserved outcome group shows a relatively narrower and more concentrated distribution along this axis (Figure 3). Although there was no statistical significance in the long term, patients in both the deteriorated outcome and preserved outcome groups displayed a similar distribution pattern in the long-term outcomes (Figure 3).

**Table 3. Univariable and Multivariable Regression Analysis of Spinal Cord Compression Ratio as a Predictor of MBI Scores**

| **Univariable Regression Analysis (n=75)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **MBI** | **$R^2$** | **DW** | **B** | **St. error** | **β** | **t** | ***p*** | **F** |
| **Short term** | 0.14 | 1.96 | 47.16 | 15.43 | 0.38 | 3.057 | **0.003**** | 9.346 |
| **Long term** | 0.01 | 2.30 | -14.92 | 20.43 | -0.11 | -0.730 | 0.469 | 0.534 |
| **Multivariable Linear Regression Analysis in the short-term (n=75)** | | | | | | | | |
| | **$R^2$** | **DW** | **β** | **t** | ***p*** | **F** | **Tolerance** | **VIF** |
| **Model summary** | **0.28** | **2.11** | | | ***<0.001**** | **10.437** | | |
| **Age** | | | -0.38 | -3.258 | 0.002** | | 1.000 | 1.000 |

| | | | | | |
|---|---|---|---|---|---|
| **Spinal cord compression ratio** | 0.38 | 3.228 | 0.002** | 1.000 | 1.000 |
| **Sex** | 0.02 | 0.154 | 0.878 | 0.996 | 1.004 |
| **Duration (months)** | -0.10 | -0.826 | 0.413 | 0.852 | 1.174 |
| **Type of CP** | 0.09 | 0.809 | 0.422 | 0.999 | 1.001 |

***Note. DW indicates Durbin-Watson. B indicates regression coefficient. St. error indicates standard error. β indicates standardized coefficient.***
***p < 0.05, **p < 0.01, ***p<0.001.***

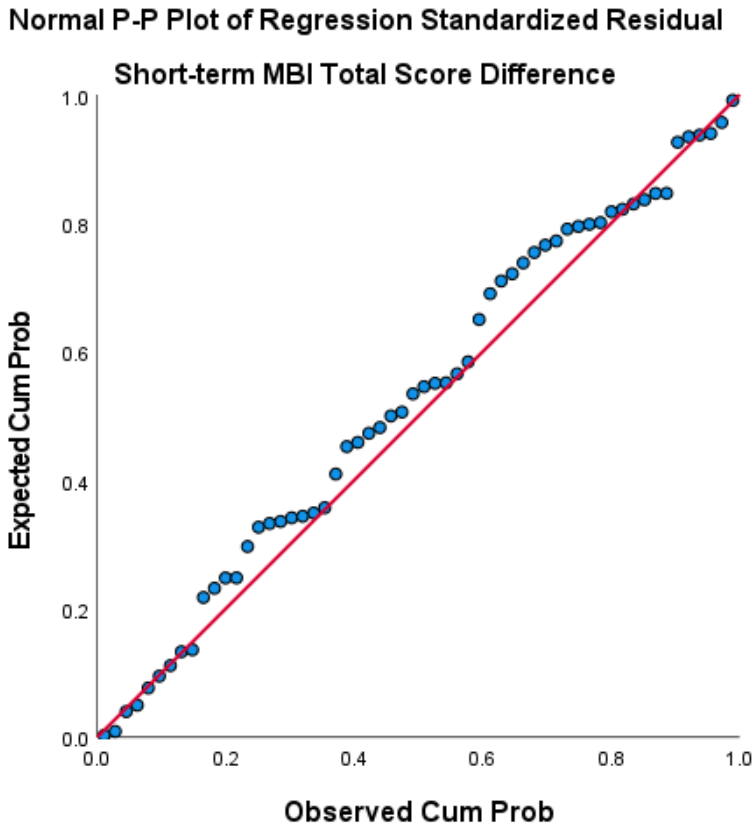


**Figure 2. Normal P-P Plot demonstrating Regression Standardized Residuals for the Model Predicting Short-Term MBI Total scores based on multivariable linear regression.**

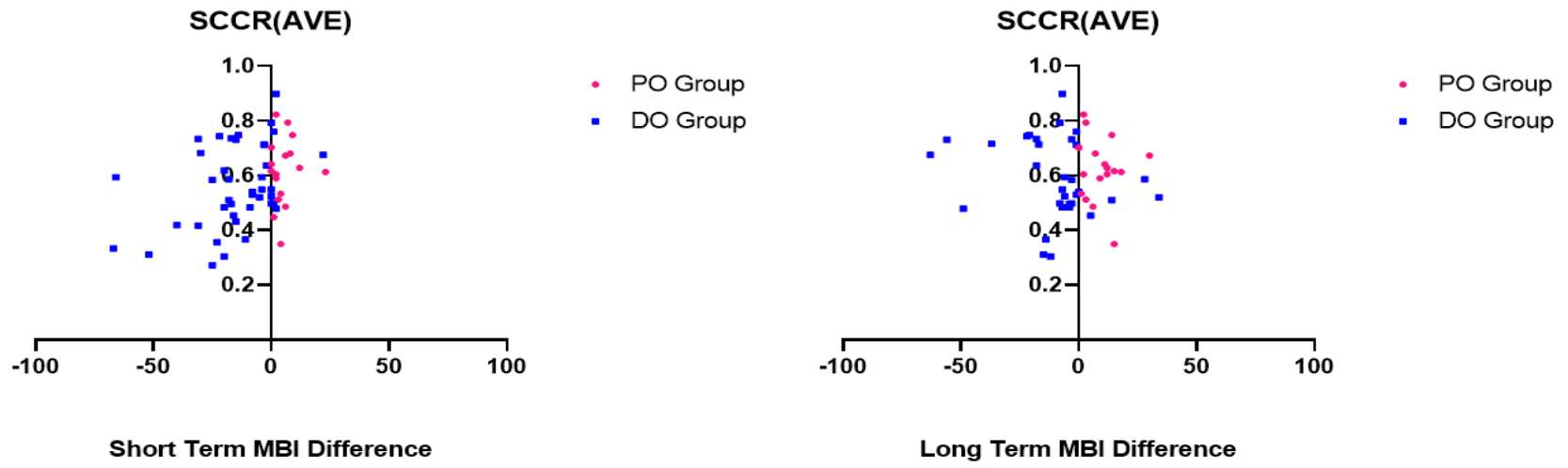


**Figure 3. Scatter graph of OP patients in accordance to their groups based on the degree of change in short-term and long-term MBI total score difference, with spinal cord compression ratio as the independent variable.**

## 2. Type of CP is a strong significant prognostic factor of post-surgical functional outcome in the long term.

Univariable regression analysis was conducted to evaluate the relationship between the type of CP as the independent variable and MBI total score (Table 4). For short-term MBI scores, type of CP did not demonstrate a significant association ($B$=1.41, standard error = 4.78, $\beta$=0.04, $t$=0.950, $p$=0.769) (Table 4). The model explained only 0.2% of the variance in short-term MBI scores ($R^2$=0.002) and had a DW value of 1.74, indicating no substantial autocorrelation in the residuals. The regression model was not statistically significant ($F$=0.087, $p$=0.769) (Table 4).

For long-term MBI scores, however, type of CP showed a significant positive association ($B$=12.74, standard error = 5.46, $\beta$=0.32, $t$=2.334, $p$=0.024) (Table 4). The model explained approximately 10.4% of the variance in long-term MBI scores ($R^2$=0.10) and had a DW value of 2.14, suggesting no issues with autocorrelation. The regression

model was statistically significant ($F$=5.446, $p$=0.024) (Table 4). These findings suggest that the type of CP may not be a meaningful predictor of short-term MBI scores in this model but is significantly associated with long-term functional outcomes. Individuals with dyskinetic CP may have a worse prognosis for long-term functional recovery compared to other types of CP in this cohort.

Multivariable linear regression analysis was also conducted to confirm the relationship between type of CP and long-term MBI total scores in post-surgery patients, while controlling for other variables including age, sex, duration of symptoms, and spinal cord compression ratio (Table 4). The overall regression model was statistically significant ($F$=6.502, $p$=0.014) and explained 12.4% of the variance in long-term MBI scores ($R^2$=0.12), with a DW value of 2.13, indicating no substantial autocorrelation in the residuals (Table 4).

Among the predictors, dyskinetic type of CP was significantly associated with long-term MBI scores ($\beta$=0.35, $t$=2.550, $p$=0.014).

This result is explained by the coding of CP types, where the dyskinetic type was coded as 0 and the spastic type as 1, reflecting a negative association with higher long-term MBI scores in dyskinetic CP patients. Other variables, including age ($\beta$= -0.01, $t$= -0.103, $p$=0.919), spinal cord compression ratio ($\beta$= -0.10, $t$= -0.688, $p$=0.495), sex ($\beta$=0.10, $t$=0.750, $p$=0.457), and duration of symptoms ($\beta$=0.17, $t$=1.268, $p$=0.211), were not significant predictors. Tolerance and VIF for all predictors were within acceptable ranges, indicating no issues with multicollinearity (Table 4).

The normal P-P plot of regression standardized residuals for the model examining the type of CP as a predictor of long-term MBI total score differences demonstrated that the residuals closely followed the diagonal regression line (Figure 4), indicating an approximate normality of residuals. This supports the validity of the regression model and confirms that the assumption of normality for residuals has been satisfied (Figure 4). Therefore the role of CP can be validated as a

significant predictor of long-term functional outcomes, highlighting its relevance in the recovery trajectory of CP patients with cervical myelopathy who underwent spinal fusion surgery.

There was no apparent significant difference in the short-term MBI score difference between individuals with dyskinetic CP and spastic CP (Figure 5). Both groups displayed similar range of score differences and interquartile ranges, implying a comparable short-term functional outcomes between the two CP types (Figure 5). A similar pattern was observed for long-term MBI score differences (Figure 5). These results show that both types of CP showed no significant impact on the long-term MBI score changes (Figure 5).

**Table 4. Univariate regression analysis for MBI score differences with CP subtype being the independent variable.**

| Univariable Regression Analysis (n=75) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **MBI** | **$R^2$** | **DW** | **B** | **St. error** | **β** | **t** | ***p*** | **F** |
| **Short term** | 0.002 | 1.74 | 1.41 | 4.78 | 0.04 | 0.950 | 0.769 | 0.087 |
| **Long term** | 0.104 | 2.14 | 12.74 | 5.46 | 0.32 | 2.334 | 0.024* | 5.446 |

| Multivariable Linear Regression Analysis in the long-term (n=75) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **$R^2$** | **DW** | **β** | **t** | ***p*** | **F** | **Tolerance** | **VIF** |
| **Model summary** | **0.12** | **2.13** | | | ***0.014**** | **6.502** | | |
| **Age** | | | -0.01 | -0.103 | 0.919 | | 0.987 | 1.003 |

| | | | | | |
|---|---|---|---|---|---|
| **Spinal cord compression ratio** | -0.10 | -0.688 | 0.495 | 0.995 | 1.005 |
| **Sex** | 0.10 | 0.750 | 0.457 | 1.000 | 1.000 |
| **Duration of symptoms (months)** | 0.17 | 1.268 | 0.211 | 1.000 | 1.000 |
| **Type of CP** | 0.35 | 2.550 | 0.014* | 1.000 | 1.000 |

***Note. DW indicates Durbin-Watson. B indicates regression coefficient. St. error indicates standard error. β indicates standardized coefficient.***
***p < 0.05, **p < 0.01, ***p<0.001.***

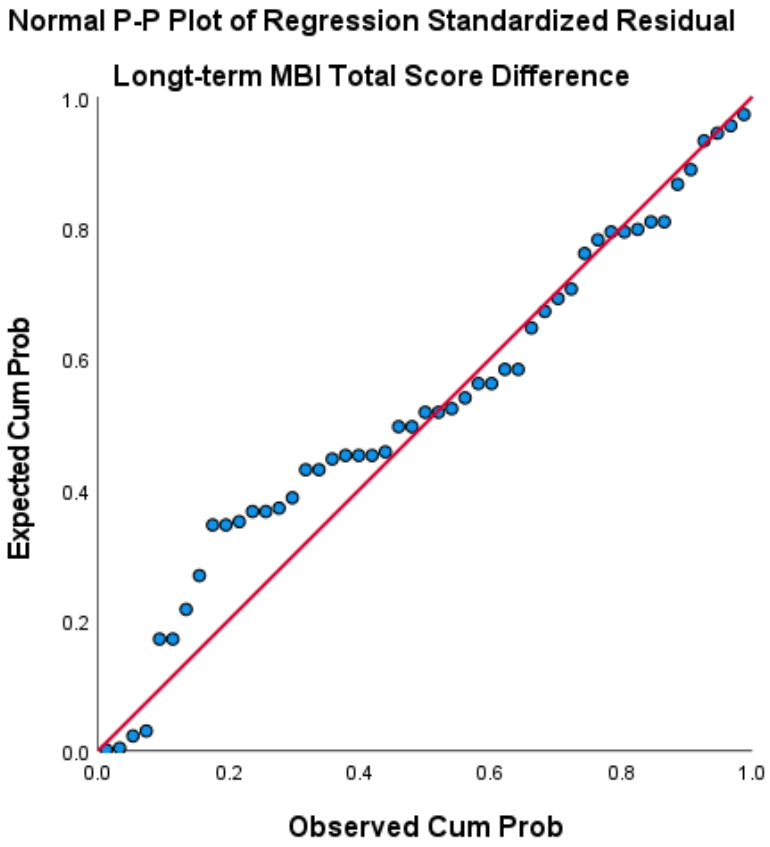


**Figure 4. Normal P-P plot displaying patient distribution over long-term MBI Total score difference.**

### 3. Duration of symptoms is a weak but significant prognostic factor of post-surgical functional outcome.

Longer symptom duration negatively impacts the recovery of functional status post-surgery, implying that CP patients who experience cervical myelopathy for extended periods before surgery tend to have worse post-surgical rehabilitation outcomes over short term ($\beta$ = -0.30, p=0.023) (Table 5, Figure 5). Univariable and multivariable linear regression analysis in the short-term and long-term for duration of symptoms did not reveal any statistical significance (Table 5). Greater proportion of patients in deteriorated outcome Group shows a wider distribution along the longer duration of symptoms axis, in the short term (Figure 5). Although there has not been statistical significance in the long term, patients in deteriorated outcome and preserved outcome group show similar distribution pattern. (Figure 5).

**Table 5. Univariate regression analysis for short term and long term MBI scores with duration of symptoms as a single independent variable.**

| Univariable Regression Analysis for MBI Scores with Duration of Symptom as Independent Variable (n=75) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **MBI** | **$R^2$** | **DW** | **B** | **St. error** | **β** | **t** | ***p*** | **F** |
| **Short term** | 0.088 | 1.73 | -0.04 | 0.02 | -0.30 | -2.345 | 0.023* | 5.498 |
| **Long term** | 0.025 | 2.20 | 0.03 | 0.03 | 0.16 | 1.114 | 0.271 | 1.241 |

***Note. DW indicates Durbin-Watson. B indicates regression coefficient. St. error indicates standard error. β indicates standardized coefficient.***
***p < 0.05, **p < 0.01, ***p<0.001.***

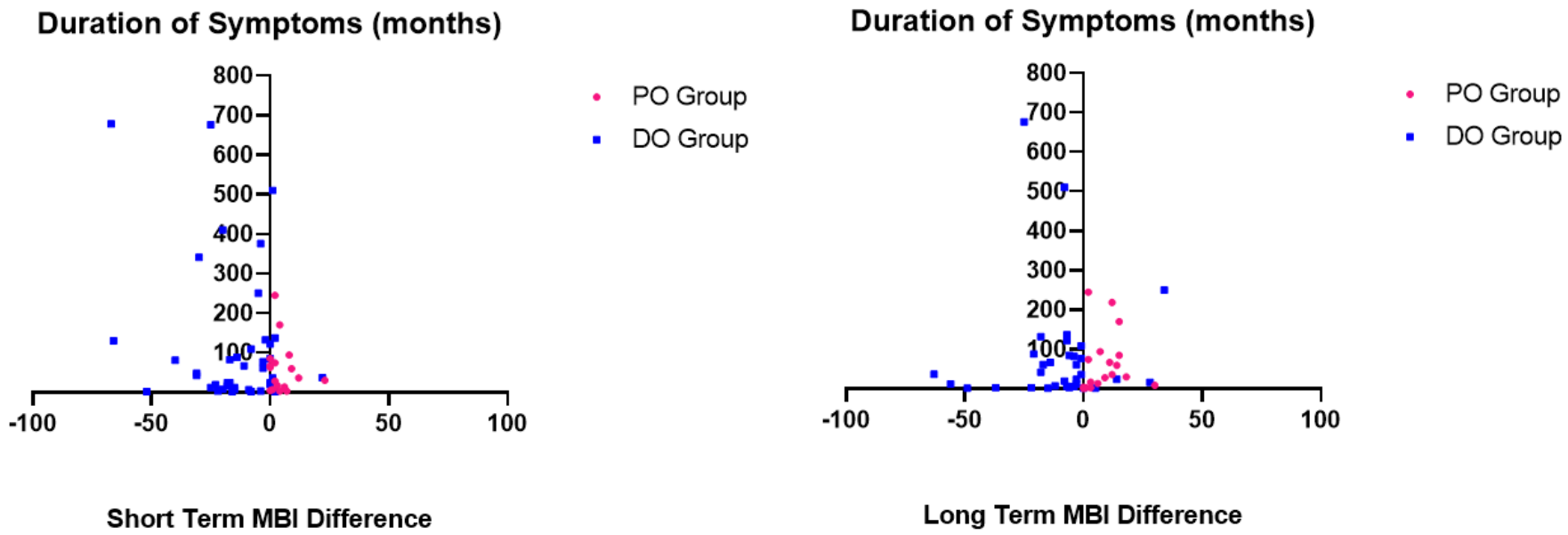


**Figure 5. Patient distribution data concerning duration of symptoms in short term and long term in accordance to MBI differences.**

## IV. DISCUSSION

The findings of this study provide novel insights into the potential prognostic factors influencing functional recovery in CP patients with cervical myelopathy undergoing spinal fusion surgery. The emphasis on spinal cord compression ratio and type of CP as primary predictors, rather than traditional metrics like the modified Japanese Orthopaedic Association (mJOA) score, represents a significant shift in the perspective at which the rehabilitative progress should be viewed. While the mJOA score is a widely recognized well-established tool for evaluating neurological deficits in cervical myelopathy, its utility in CP patients is limited due to the baseline neurological impairments inherent to this population and may also be subjected to cultural variance [30]. Components of mJOA are not well correlated to other metrics such as Neck Disability Index [31]. Unlike subjective clinical scoring systems, spinal cord compression ratio is derived from imaging data and undeniably reflects the anatomical state of the spinal cord [32-34]. This eliminates variability in interpretation and provides surgeons with a

reliable indicator of the extent of spinal cord compression. spinal cord compression ratio, as a direct and pronounced radiological measure of biomechanical compression, thus offers a more objective and specific quantification metrics that is especially relevant in predicting surgical outcomes in CP patients with cervical myelopathy.

The study's findings confirm that spinal cord compression ratio is a strong significant independent predictor of postoperative MBI scores. Higher spinal cord compression ratio values, indicative of less severe spinal cord compression, were associated with improved functional outcomes. This positive correlation also highlights the critical importance of addressing spinal cord compression through timely surgical intervention, reducing the biomedical impact that helps redistribute loading in the cervical region [35, 36]. Tissue stress can therefore be relieved with relief of deformative forces along axial alignment of the spine [37, 38]. By restoring the biomechanical dynamic balance, patients will be able to experience reduction in pain and overcome sensory deficits, while securing motor control ability from

further deterioration through hypertrophy in the long run. The findings from this study thus suggest that spinal cord compression ratio could be further explored as a criterion for surgical candidacy in CP patients, particularly those presenting with ambiguous clinical symptoms that overlap with cervical myelopathy. Furthermore, its applicability to both CP patients and the general population with cervical myelopathy underscores its versatility and relevance in clinical practice.

The study also revealed a significant negative correlation between duration of symptoms and postoperative MBI scores, highlighting the detrimental impact of delaying surgical intervention. Prolonged duration of symptoms likely intensifies neuronal damage due to chronic spinal cord compression, whereby hypertrophy leads to irreversible functional deficits over time. When the spinal cord is subjected to sustained pressure, it undergoes progressive ischemia and demyelination, impairing the ability of nerve cells to transmit signals effectively[39]. This can be particularly detrimental to CP patients who are already facing a disadvantageous motor and sensory dysfunction

due to their poor orientation of spinal vertebrae. Once damage reaches a critical threshold, the potential for recovery may diminish significantly even after surgical decompression as adjacent neural integrity cannot be fully salvaged [40-42].

This finding aligns with already established neuroprotective principles, which emphasize the critical importance of early intervention to preserve neuronal integrity and prevent permanent neurological decline [42, 43]. For patients with CP, the implications are particularly profound as they often present with complex and multifaceted symptoms that can obscure the early signs of cervical myelopathy, such as worsening gait instability or subtle reduction in dexterity of the hands [44, 45]. Delayed diagnosis and treatment can further exacerbate these challenges, as ongoing spinal cord compression adds onto the pre-existing motor and functional deficits caused by CP itself [46, 47].

Another important aspect of this study is the clear classification

of type of CP as the contributing prognosis factor. A recent 2024 study by Yang et al analyzed athetoid CP patients who underwent cervical spinal fusion surgery, revealing that the anterior fusion alone had the highest revision rate at 42.7% [48]. Combined anterior-posterior fusion surgery, however, resulted in the lowest revision rate at 11.1% hence proving its higher durability in this patient population [48]. CP subtypes are therefore a chief prognostic factor in predicting the result of spinal fusion surgery and even other related surgeries involving the relief of compression. Patients with dyskinetic CP may experience a worse prognosis as this particular subtype mostly affects movement control rather than muscle strength or structure. Their spine may not be fully stabilized from a single episode of surgery; abnormal movements may not be corrected due the consistent uncontrolled movement in the surgical region leading to gradual loosening of the screw [49]. Fractures may be induced on the vertebrae on top or bottom of the screw, resulting in subsequent surgeries to be even more difficult [49]. Should cervical myelopathy be present in multiple vertebrae, wider affected area may

require even more intensive post-surgical rehabilitation in patients with this type of CP.

The study accentuates the need for more comprehensive clinical interpretation and timely intervention from diagnosis to treatment. For patients and their caregivers, this means understanding that postponing surgery in the presence of progressive motor or sensory deficits may significantly reduce the chances of achieving a successful recovery. Each additional month of untreated compression increases the likelihood of permanent disability, hence limiting independence in daily activities such as walking, dressing, or feeding.

From a practical perspective, it is essential for patients to recognize that earlier surgical intervention not only halts further damage but also optimizes the chances for meaningful functional recovery. Future research could explore the concept of specific duration of symptoms thresholds—critical time windows within which surgery is most beneficial—potentially guiding standardized timelines for

intervention. For now, the evidence strongly advocates for prioritizing early diagnosis and prompt treatment to protect long-term quality of life.

One of the most novel aspects of this study is the combined predictive value of spinal cord compression ratio, CP subtype and duration of symptoms. While these variables have been individually validated in the general population with cervical myelopathy or among CP patients without symptomatic spinal cord compression, their interaction in this unique population represents an important area of investigation. Not only does this model consist of a very forthright radiologic parameter spinal cord compression ratio, but also integrate clinical classification and demographic metrics. Such a holistic model offers a robust tool for clinical decision-making.

By integrating spinal cord compression ratio, type of CP and duration of symptoms, clinicians can better stratify patients based on their risk profiles and optimize the timing of surgical interventions. This combined approach not only enhances the precision of preoperative

counseling but also informs postoperative rehabilitation strategies tailored to the unique needs of CP patients.

**Limitations and Future Directions**

While the study provides valuable insights, several limitations warrant consideration. First, the small sample size may limit the generalizability of the findings to the broader CP population. Future studies with larger and more diverse cohorts are needed to validate the predictive model and refine its applicability. Second, the study focuses exclusively on spinal cord compression ratio, type of CP and duration of symptoms, while other potential predictors, such as location of cervical myelopathy, range of cervical myelopathy, level of hand dexterity, nutritional status, comorbidities, and socioeconomic factors, remain unexplored. Incorporating additional biomarkers and clinical parameters into the predictive model could enhance its accuracy and utility. Moreover, the study's reliance on MBI as the sole measure of functional recovery, while holistically practical, may not fully capture the delicate changes in motor and sensory functions specific to CP patients. Future research should consider incorporating complementary outcome measures, such as gait analysis and quality-of-life assessments, to provide a more

comprehensive evaluation of recovery. Lastly, longitudinal studies tracking functional outcomes beyond the immediate to intermediate postoperative period are essential to understanding the longer term implications of spinal cord compression ratio, type of CP and duration of symptoms on quality of life and level of functional independence.

## V. Conclusion

In conclusion, this study advances our understanding of the factors influencing functional recovery in CP patients with cervical myelopathy undergoing spinal fusion surgery. By highlighting the combined predictive value of spinal cord compression ratio and duration of symptoms, it paves the way for more targeted and effective clinical interventions. Future research should build on these findings to develop comprehensive predictive models that incorporate a broader range of variables, ultimately enhancing the quality of care for this vulnerable population.

## References

1. Jones MW, Morgan E, Shelton JE, et al. Cerebral Palsy: Introduction and Diagnosis (Part I). *Journal of Pediatric Health Care* 2007; 21: 146-152. DOI: https://doi.org/10.1016/j.pedhc.2006.06.007.

2. Krigger KW. Cerebral palsy: an overview. *Am Fam Physician* 2006; 73: 91-100. 2006/01/19.

3. McIntyre S, Goldsmith S, Webb A, et al. Global prevalence of cerebral palsy: A systematic analysis. *Dev Med Child Neurol* 2022; 64: 1494-1506. 2022/08/12. DOI: 10.1111/dmcn.15346.

4. Stavsky M, Mor O, Mastrolia SA, et al. Cerebral Palsy—Trends in Epidemiology and Recent Development in Prenatal Mechanisms of Disease, Treatment, and Prevention. *Frontiers in Pediatrics* 2017; 5. Review. DOI: 10.3389/fped.2017.00021.

5. Graham HK and Selber P. MUSCULOSKELETAL ASPECTS OF CEREBRAL PALSY. *The Journal of Bone & Joint Surgery British Volume* 2003; 85-B: 157-166. DOI: 10.1302/0301-620x.85b2.14066.

6. Reid SM, Dagia CD, Ditchfield MR, et al. Population-based studies of brain imaging patterns in cerebral palsy. *Developmental Medicine & Child Neurology* 2014; 56: 222-232. DOI: https://doi.org/10.1111/dmcn.12228.

7. Islam M, Nordstrand L, Holmström L, et al. Is outcome of constraint-induced movement therapy in unilateral cerebral palsy dependent on corticomotor projection pattern and brain lesion characteristics? *Developmental Medicine & Child Neurology* 2014; 56: 252-258. DOI: https://doi.org/10.1111/dmcn.12353.

8. te Velde A, Morgan C, Novak I, et al. Early Diagnosis and Classification of Cerebral Palsy: An Historical Perspective and Barriers to an Early Diagnosis. *J Clin Med* 2019; 8 2019/10/19. DOI: 10.3390/jcm8101599.

9. Reid SM, Carlin JB and Reddihough DS. Classification of topographical pattern of spasticity in cerebral palsy: A registry perspective. *Research in Developmental Disabilities* 2011; 32: 2909-2915. DOI: https://doi.org/10.1016/j.ridd.2011.05.012.

10. BARRETT RS and LICHTWARK GA. Gross muscle morphology and structure in spastic cerebral palsy: a systematic review. *Developmental Medicine & Child Neurology* 2010; 52: 794-804. DOI: https://doi.org/10.1111/j.1469-8749.2010.03686.x.

11. Fergus A. A Novel Mobility Device to Improve Walking for a Child With Cerebral Palsy. *Pediatric Physical Therapy* 2017; 9.

12. Jameson R, Rech C and Garreau de Loubresse C. Cervical myelopathy in athetoid and dystonic cerebral palsy: retrospective study and literature review. *Eur Spine J* 2010; 19: 706-712. 2010/01/13. DOI: 10.1007/s00586-009-1271-7.

13. Harrop JS, Hanna A, Silva MT, et al. NEUROLOGICAL MANIFESTATIONS OF CERVICAL Spreserved outcomeNDYLOSIS: AN OVERVIEW OF SIGNS, SYMPTOMS, AND PATHOPHYSIOLOGY. *Neurosurgery* 2007; 60: S1-14-S11-20. DOI: 10.1227/01.Neu.0000215380.71097.Ec.

14. Baptiste DC and Fehlings MG. Pathophysiology of cervical myelopathy. *The Spine Journal* 2006; 6: S190-S197. DOI: https://doi.org/10.1016/j.spinee.2006.04.024.

15. Endo T, Sugawara T and Higashiyama N. Cervical myelopathy due to neurovascular compression syndrome caused by persistent first intersegmental artery: a case report. *BMC Neurology* 2020; 20: 402. DOI: 10.1186/s12883-020-01976-x.

16. Suri A, Chabbra RP, Mehta VS, et al. Effect of intramedullary signal

changes on the surgical outcome of patients with cervical spondylotic myelopathy. *Spine J* 2003; 3: 33-45. 2003/11/01. DOI: 10.1016/s1529-9430(02)00448-5.

17. Takahashi K, Ozawa H, Sakamoto N, et al. Influence of intramedullary stress on cervical spondylotic myelopathy. *Spinal Cord* 2013; 51: 761-764. DOI: 10.1038/sc.2013.94.

18. Misawa T, Kamimura M, Kinoshita T, et al. Neurogenic Bladder in Patients with Cervical Compressive Myelopathy. *Clinical Spine Surgery* 2005; 18: 315-320. DOI: 10.1097/01.bsd.0000166638.31398.14.

19. Edwards CC, Riew KD, Anderson PA, et al. Cervical myelopathy: current diagnostic and treatment strategies. *The Spine Journal* 2003; 3: 68-81. DOI: https://doi.org/10.1016/S1529-9430(02)00566-1.

20. Kang KC, Jang TS, Choi SH, et al. Difference between Anterior and Posterior Cord Compression and Its Clinical Implication in Patients with Degenerative Cervical Myelopathy. *J Clin Med* 2023; 12 2023/06/28. DOI: 10.3390/jcm12124111.

21. Ahn J-S, Lee J-K and Kim B-K. Prognostic Factors That Affect the Surgical Outcome of the Laminoplasty in Cervical Spondylotic Myelopathy. *Clinics in orthopedic surgery* 2010; 2: 98-104. DOI: 10.4055/cios.2010.2.2.98.

22. Kadanka Z, Jr., Adamova B, Kerkovsky M, et al. Predictors of symptomatic myelopathy in degenerative cervical spinal cord compression. *Brain Behav* 2017; 7: e00797. 2017/09/28. DOI: 10.1002/brb3.797.

23. Tetreault L, Wilson JR, Kotter MRN, et al. Is Preoperative Duration of Symptoms a Significant Predictor of Functional Outcomes in Patients Undergoing Surgery for the Treatment of Degenerative Cervical Myelopathy? *Neurosurgery* 2019; 85: 642-647. 2018/11/18. DOI: 10.1093/neuros/nyy474.

24. Jiang Z, Davies B, Zipser C, et al. The Frequency of Symptoms in Patients

With a Diagnosis of Degenerative Cervical Myelopathy: Results of a Scoping Review. *Global Spine J* 2024; 14: 1395-1421. 2023/11/02. DOI: 10.1177/21925682231210468.

25. Monbaliu E, Himmelmann K, Lin J-P, et al. Clinical presentation and management of dyskinetic cerebral palsy. *The Lancet Neurology* 2017; 16: 741-749. DOI: 10.1016/S1474-4422(17)30252-1.

26. Lumsden DE, Kaminska M, Gimeno H, et al. Proportion of life lived with dystonia inversely correlates with response to pallidal deep brain stimulation in both primary and secondary childhood dystonia. *Dev Med Child Neurol* 2013; 55: 567-574. 2013/03/05. DOI: 10.1111/dmcn.12117.

27. Hukuda S, Mochizuki T, Ogata M, et al. Operations for cervical spondylotic myelopathy. A comparison of the results of anterior and posterior procedures. *J Bone Joint Surg Br* 1985; 67: 609-615. 1985/08/01. DOI: 10.1302/0301-620x.67b4.4030860.

28. Tanaka J, Seki N, Tokimura F, et al. Operative results of canal-expansive laminoplasty for cervical spondylotic myelopathy in elderly patients. *Spine (Phila Pa 1976)* 1999; 24: 2308-2312. 1999/12/10. DOI: 10.1097/00007632-199911150-00004.

29. Lee JJ, Shin DA, Yi S, et al. Effect of posterior instrumented fusion on three-dimensional volumetric growth of cervical ossification of the posterior longitudinal ligament: a multiple regression analysis. *The Spine Journal* 2018; 18: 1779-1786. DOI: https://doi.org/10.1016/j.spinee.2018.03.002.

30. Fawaz SI, Elgebeily MA, Saber HG, et al. The Reliability of an Arabic Version of the Modified Japanese Orthopaedic Association Score for Cervical Myelopathy. *Spine Surg Relat Res* 2021; 5: 149-153. 2021/06/29. d DOI: 10.22603/ssrr.2020-0121.

31. Kopjar B, Tetreault L, Kalsi-Ryan S, et al. Psychometric Properties of the Modified Japanese Orthopaedic Association Scale in Patients With Cervical Spondylotic Myelopathy. *Spine* 2015; 40: E23-E28. DOI: 10.1097/brs.0000000000000648.

32. Hilton B, Tempest-Mitchell J, Davies BM, et al. Cord compression defined by MRI is the driving factor behind the decision to operate in Degenerative Cervical Myelopathy despite poor correlation with disease severity. *PLoS One* 2019; 14: e0226020. 2019/12/27. DOI: 10.1371/journal.pone.0226020.

33. Tempest-Mitchell J, Hilton B, Davies BM, et al. A comparison of radiological descriptions of spinal cord compression with quantitative measures, and their role in non-specialist clinical management. *PLoS One* 2019; 14: e0219380. 2019/07/23. DOI: 10.1371/journal.pone.0219380.

34. Hong K-U, Jung J-m, Hyun S-J, et al. Radiologic Factors for Predicting Dynamic Spinal Cord Compression in Conventional Cervical MRI. *J Neurointensive Care* 2019; 2: 58-63. DOI: 10.32587/jnic.2019.00192.

35. Denaro V and Di Martino A. Cervical spine surgery: an historical perspective. *Clin Orthop Relat Res* 2011; 469: 639-648. 2011/01/08. deteriorated outcome DOI: 10.1007/s11999-010-1752-3.

36. Suen T-K, Wong K-H and Ho Y-F. The Outcomes of Anterior Spinal Fusion for Cervical Compressive Myelopathy—A Retrospective Review. *Journal of Orthopaedics, Trauma and Rehabilitation* 2011; 15: 53-56. DOI: https://doi.org/10.1016/j.jotr.2011.04.003.

37. Liang W, Xiong Y, Jia Y, et al. Anterior cervical discectomy and fusion for the treatment of giant cervical disc herniation. *Journal of Orthopaedic Surgery and Research* 2023; 18: 683. DOI: 10.1186/s13018-023-04036-5.

38. Yoshii T, Egawa S, Chikuda H, et al. Comparison of anterior

decompression with fusion and posterior decompression with fusion for cervical spondylotic myelopathy—A systematic review and meta-analysis. *Journal of Orthopaedic Science* 2020; 25: 938-945. DOI: https://doi.org/10.1016/j.jos.2019.12.010.

39. Vargas MI, Gariani J, Sztajzel R, et al. Spinal cord ischemia: practical imaging tips, pearls, and pitfalls. *AJNR Am J Neuroradiol* 2015; 36: 825-830. 2014/10/18. DOI: 10.3174/ajnr.A4118.

40. Hasan MT, Patil S, Chauhan V, et al. Spinal cord compression from hypertrophic nerve roots in chronic inflammatory demyelinating polyradiculoneuropathy - A case report. *Surg Neurol Int* 2021; 12: 114. 2021/04/22. DOI: 10.25259/sni_35_2021.

41. Maurice-Williams RS and Garlick R. Spinal cord compression caused by bilateral nerve root hypertrophy. *Surgical Neurology* 1989; 31: 465-467. DOI: https://doi.org/10.1016/0090-3019(89)90093-1.

42. Kim MW, Kang CN and Choi SH. Update of the Natural History, Pathophysiology, and Treatment Strategies of Degenerative Cervical Myelopathy: A Narrative Review. *Asian Spine J* 2023; 17: 213-221. 2023/02/15. DOI: 10.31616/asj.2022.0440.

43. Tetreault L, Kalsi-Ryan S, Benjamin D, et al. Degenerative Cervical Myelopathy: A Practical Approach to Diagnosis. *Global Spine Journal* 2022; 12: 1881-1893. DOI: 10.1177/21925682211072847.

44. Golubović Š and Slavković S. Manual ability and manual dexterity in children with cerebral palsy. *Hippokratia* 2014; 18: 310-314. 2015/06/09.

45. Park ES, Sim EG and Rha D-w. Effect of upper limb deformities on gross motor and upper limb functions in children with spastic cerebral palsy. *Research in Developmental Disabilities* 2011; 32: 2389-2397. DOI:

https://doi.org/10.1016/j.ridd.2011.07.021.

46. Pope DH, Mowforth OD, Davies BM, et al. Diagnostic Delays Lead to Greater Disability in Degenerative Cervical Myelopathy and Represent a Health Inequality. *Spine (Phila Pa 1976)* 2020; 45: 368-377. 2019/10/29. DOI: 10.1097/brs.0000000000003305.

47. Behrbalk E, Salame K, Regev GJ, et al. Delayed diagnosis of cervical spondylotic myelopathy by primary care physicians. *Neurosurg Focus* 2013; 35: E1. 2013/07/03. DOI: 10.3171/2013.3.Focus1374.

48. Yang JJ, Choi JY, Lee DH, et al. Reoperation Rates According to Surgical Approach After Operation for Degenerative Cervical Pathology in Patients With Athetoid Cerebral Palsy: A Nationwide Cohort Study. *Global Spine J* 2024: 21925682241247486. 2024/04/18. DOI: 10.1177/21925682241247486.

49. Kim HC, Jeon H, Jeong YH, et al. Factors Affecting Postoperative Complications and Outcomes of Cervical Spondylotic Myelopathy with Cerebral Palsy : A Retrospective Analysis. *J Korean Neurosurg Soc* 2021; 64: 808-817. DOI: 10.3340/jkns.2021.0012.

## ABSTRACT (KOREAN)

# 경추 척수증을 동반한 뇌성마비 환자의 척추 유합술의 재활 예후 예측

<지도교수 조성래>

연세대학교 일반대학원 생체공학협동과정

황 지 혜

운동 기능 장애를 특징으로 하는 이질적인 신경 발달 장애인 뇌성마비(CP)는 만성 척수 압박으로 인해 발생하는 질환인 경추 척수증과 복합적으로 작용할 때 더욱 심각한 문제를 야기한다. 경추 척수증은 CP의 전형적인 증상들과 겹치기 때문에 해당 환자군에서 진단이 지연될 수 있고 적절한 시기 내에 치료가 진행되지 못하여 심각한 운동 및 감각 장애를 초래하는 경우가 많다. 해당 연구는 척수 압박 비율, 증상 지속 기간, CP 아형이 척추 유합술을 받은 CP 환자의 수술 후 기능적 결과에 미치는 예측 가치를 평가하는 것을 목표로 하며 해당 연구를 통해 낮은 척수 압박 비율, 긴 증상 지속 기관 그리고 운동이상형 CP가 회복에 부정적인 영향을 미칠 것이라는 가설을 세워 일상 생활 활동의 독립성을 측정하는 수정 바델 지수(MBI)인 기능적 결과를 사용하여 평가했다. 연구 결과 척수 압박 비율이 유의미한 독립 예측 인자로 확인되었으며 척수 압박 비율이 높을수록 수술 후 기능 개선과 관련이 있는 것으로 나타났다. 반대로 증상이 오래 지속되면 비가학적 신경세포 손상이 발생할 확률이 높아지기에 적시에 수술적 개입이 매우 중요하다는

것을 강조했습니다. 운동이상형 CP는 경추 부위의 비정상적인 감각 운동 통합과 통제되지 않는 움직임으로 인해 수술 안정성을 저해하고 보다 집중적인 재활이 필요한 예후 불량 요인으로 사료된다. 이에 본 연구 결과는 수술 결과를 최적화하고 장기적인 장애를 예방하기 위해 경추 척수증 환자의 조기 진단과 개입이 필요하다는 점과 척수 압박 비율, 증상 지속 시간 및 CP 유형과 함께 수술 전 상담 및 수술 후 계획에 중요성을 밝혔다. 따라서 재활의학적 측면의 회복을 예측할 때 방사선학적, 임상적, 인구통계학적 요인의 상호 작용을 밝혀 CP 환자의 척추 유합술에 대한 총체적인 접근 방식의 중요성을 강조한다.

---

핵심되는 말: 뇌성마비, 경추 척수증, 척수 압박 비율, 운동 이상, 증상 지속 시간

## PUBLICATIONS LIST

1. Yeo, M. S.*, **Hwang, J.*,** Lee, H. K., Kim, S. J., & Cho, S.-R. (2024, March 18). *Therapeutic singing-induced swallowing exercise for dysphagia in advanced-stage parkinson's disease*. Frontiers in Neurology. https://doi.org/10.3389/fneur.2024.1323703 ***Co-first authors***

2. Lee, H. K.*, **Hwang, J.*,** Jo, S., & Cho, S.-R. (2024, November 5). *Adhesion Reduction Agent Guardix-SG® Versus MegaShield® for Postoperative Swallowing Function Analysis in Thyroidectomy Patients.* Clinical Medicine Insights: Oncology. https://doi.org/10.1177/117955492412717 ***Co-first authors***

3. Kim, K. M., Lee, T. K., Lee, S. M., Chang, W. S., Lee, S. J., **Hwang, J.***, & Cho, S.-R*. (2024, January 22). *Case report: Intrathecal baclofen therapy improved gait pattern in a stroke patient with spastic dystonia*. Frontiers in Neurology. https://doi.org/10.3389/fneur.2024.1330811 ***Co-corresponding authors***

4. Jo, S., Baek, A., Cho, Y., Kim, S. H., Baek, D., **Hwang, J.,** Cho, S.-R.*, & Kim, H. J*. (2023, April 12). *Therapeutic effects of polydeoxyribonucleotide in an in vitro neuronal model of ischemia/reperfusion injury*. Scientific Reports. https://doi.org/10.1038/s41598-023-32744-9 ***Co-corresponding authors***

5. Lee, H. Y., Song, S.-Y., **Hwang, J**., Baek, A., Baek, D., Kim, S. H., Park, J. H., Choi, S., Pyo, S., & Cho, S.-R. (2022, December 29). *Very early environmental enrichment protects against apoptosis and improves functional recovery from hypoxic–ischemic brain injury*. Frontiers in Molecular Neuroscience. https://doi.org/10.3389/fnmol.2022.1019173

6. Pyo, S., Kim, J., **Hwang, J.**, Heo, J. H., Kim, K., & Cho, S.-R. (2022, March 21). *Environmental enrichment and estrogen upregulate beta-hydroxybutyrate underlying functional improvement*. Frontiers in Molecular Neuroscience. https://www.frontiersin.org/journals/molecular-neuroscience/articles/10.3389/fnmol.2022.869799/full