European Spine Journal
https://doi.org/10.1007/s00586-025-09134-y

RESEARCH

Identifying biomechanical and neurophysiological risk factors for postoperative neurologic deterioration in OPLL surgery: A study using ROC curve and path analysis

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Received: 31 March 2025 / Revised: 30 June 2025 / Accepted: 7 July 2025

Abstract

Objective Ossification of the posterior longitudinal ligament (OPLL) can lead to compressive myelopathy, which requires surgical intervention. This study aimed to evaluate biomechanical and neurophysiological predictors of postoperative motor (PMD) and sensory deterioration (PSD) in cervical OPLL surgery, with the goal of improving patient prognosis and surgical outcomes.

Methods A retrospective cohort study was conducted on 111 patients with cervical OPLL who underwent surgery with intraoperative neurophysiological monitoring during 5 years in a single institute. The axial size of OPLL, intraoperative motor evoked potential (MEP) changes, and somatosensory evoked potential (SEP) latency prolongation were analyzed using ROC curve and linear path analysis to assess their predictive value for PMD and PSD.

Results The axial size of the OPLL at each level demonstrates no significant difference, regardless of changes in SEPs or MEPs, or the presence of postoperative sensory or motor deterioration. Differences in the OPLL occupying area ratio between the C5 and C6 levels ($\Delta OPLL_{C5\text{-}C6}$ occupying area ratio) was significantly greater in patients with SEP latency prolongation ($P=0.04$) or MEP amplitude reduction ($P=0.002$). The ratio difference was also identified as a critical predictor for PMD and PSD. Receiver operating characteristic (ROC) analysis shows that $\Delta OPLL_{C5\text{-}C6}$ occupying area ratio had the highest area under the curve (AUC) for predicting significant MEP amplitude (AUC = 0.837, $p<0.001$) and SEP latency (AUC = 0.712, $p=0.015$) changes. Path analysis revealed that the $\Delta OPLL_{C5\text{-}C6}$ occupying area ratio had a significant indirect effect on PMD (B = 0.561, $p=0.002$) and PSD (B = 0.305, $p=0.034$), mediated by MEP and SEP changes, respectively.

Conclusion The $\Delta OPLL_{C5\text{-}C6}$ occupying area ratio appears to be a strong predictor of PMD and PSD in cervical OPLL surgery, potentially influencing outcomes primarily through neurophysiological changes. To help mitigate postoperative neurological complications, continuous neurophysiological monitoring and targeted biomechanical assessments may be beneficial components of the surgical planning process.

Keywords Intraoperative neurophysiological monitoring · Ossification of posterior longitudinal ligament · Spine · Risk factors · Path analysis · Postoperative motor deficit

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Published online: 19 November 2025

Introduction

Ossification of the posterior longitudinal ligament (OPLL) represents an abnormal thickening of the posterior ligament, with a reported prevalence of 2–4% in Asians and 0.2–0.7% among Caucasians. OPLL is recognized as a multifactorial disease influenced by genetic determinants and environmental attributes such as young age, male gender, ethnicity, diabetes mellitus, obesity, dietary habits, sleeping duration, multi-level vertebral involvement, and a continuous type of OPLL [1–3]. Because of its relatively low prevalence, OPLL is not included as a screening element in national health examinations; therefore, diagnosing OPLL before symptom onset is challenging. Often, OPLL identification occurs inadvertently, following manifestations of neck discomfort or trauma-induced spinal cord contusion [4, 5]. Although not all cases of OPLL develop myelopathy, once diagnosed, regular follow-up is required due to its progressive potential. Therefore, the clinical importance of OPLL is not trivial, and the most troublesome symptoms, such as muscle weakness, sensory deterioration, and a neurogenic bowel and bladder, are caused by compressive myelopathy due to severe canal stenosis, resulting in a decreased quality of life. In these cases, OPLL-induced canal stenosis needs to be surgically widened to alleviate symptoms and prevent their progression [6–8].

However, surgery-induced structural changes may lead to neurophysiological deterioration, potentially resulting in more severe forms of myelopathy or radiculopathy. For instance, C5 palsy, a significant postoperative complication of cervical spinal surgery, has a prevalence of 6.3%, which rises to 8.1% in cases involving OPLL surgery [9]. The relatively narrow spinal canal at the C4/5 and C5/6 levels has been highlighted as an anatomical indication of the high prevalence of C5 palsy following cervical spinal surgery [10]. Beyond C5 palsy, iatrogenic neural injuries may emerge from various surgical interventions, either due to direct trauma or indirectly from neural decompression, leading to reperfusion injuries [11].

To enhance surgical outcomes in spinal surgery, in addition to identifying risk factors contributing to postoperative neurological deterioration (PND), intraoperative neurophysiological monitoring (IONM) is being implemented and is gradually gaining widespread acceptance [12]. Continuous monitoring of evoked potentials and electromyography may enable the early detection of electrophysiological evidence of neural injury. Recent studies have also covered the use of IONM during OPLL surgery [13, 14].

This study analyzed comprehensive risk factors for postoperative motor or sensory deterioration after OPLL surgery, focusing on demographic, radiological, and intraoperative data including IONM findings. In particular, we applied receiver operating characteristic (ROC) curve analysis and linear path analysis to investigate the contribution of biomechanical and neurophysiological features to postoperative outcomes. This study aimed to identify risk factors for postoperative neurological deterioration following OPLL surgery by analyzing the interplay between biomechanical characteristics and intraoperative neurophysiological data. In particular, we focused on dynamic biomechanical features and their influence on intraoperative responses and postoperative outcomes, an aspect that has not been fully addressed in previous research. Notably, to our knowledge, this is the first study to consider intersegmental differences in OPLL size between adjacent cervical levels as a potential risk factor.

Materials and methods

Study design and study population

In this retrospective cohort study, data were sourced from a single tertiary hospital. The research protocol, approved by the relevant institutional review board (IRB) (3–2021-0494), adhered to the Declaration of Helsinki. The IRB confirmed that informed consent was not required as the study complied with standard practice and did not expose patient-identifiable information.

Patients with cervical OPLL who underwent surgery with IONM between February 2015 and July 2019 were screened. Exclusion criteria encompassed patients showing no baseline response to intraoperative somatosensory evoked potentials (SEPs) or motor evoked potentials (MEPs); those for whom postoperative neurological status could not be assessed due to significant complications; patients who did not survive beyond 4 weeks post-surgery; and those who had another spinal surgery within 4 weeks following OPLL surgery. Neurological examinations were conducted both a day before and 48 h post-surgery. The demographic, preoperative, perioperative, and postoperative data were collected through a review of medical records, without conducting any additional prospective surveys.

Demographic data

The demographic data included age, sex, and height.

Preoperative data

Radiological parameters

Two physiatrists reviewed the computed tomography (CT) images and the flexion–extension plain images of the

cervical spine for radiological measurements. In cases of discrepancies in the measurements, they reached a consensus through discussion. Radiological parameters encompassed OPLL axial size, the longitudinal levels occupied by OPLL, and anteroposterior (AP) cervical range of motion (ROM). Radiological measurements were conducted using the Picture Archiving and Communication System (Centricity PACS, Radiology RA1000 Workstation, GE Healthcare, Barrington, IL, United States).

OPLL axial size: Using the axial view of the preoperative CT scan, measurements of the AP diameter were taken and area of both the spinal canal and OPLL at the maximal OPLL occupying image of each C2–C7 level. From these measurements, the OPLL occupying diameter and the OPLL occupying area ratios were derived as follows:

- OPLL occupying diameter ratio = OPLL AP diameter/spinal canal AP diameter
- OPLL occupying area ratio = OPLL occupying area/spinal canal area

During data analysis process, we discovered that the difference in the OPLL occupying area ratio between adjacent spinal levels is important, and we decided to describe it as follows:

- ΔOPLLCa-Cb occupying area ratio = OPLL occupying area ratio of upper level (a) – OPLL occupying area ratio of adjacent lower level (b)

e.g. $\Delta OPLL_{C5\text{-}C6}$ occupying area ratio = OPLL occupying area ratio of C5 level – OPLL occupying area ratio of C6 level (Figure 1)

OPLL occupying longitudinal levels: The number of levels occupied by OPLL was determined by analyzing the sagittal view of the CT scans.

Cervical ROM: Prior to surgery, a lateral view of the cervical spine in flexion–extension was taken to assess the range of anterior flexion and posterior extension in the neck. The APROM of the cervical spine was determined using the difference in Cobb's angle of the C2–C7 vertebrae as observed on plain lateral images.

APROM = Cobb's angle of C2–C7 in full posterior extension – Cobb's angle of C2–C7 in full anterior flexion.

Neurological examination

The medical records describing the neurological examinations, performed by a physiatrist a day prior to surgery, were reviewed.

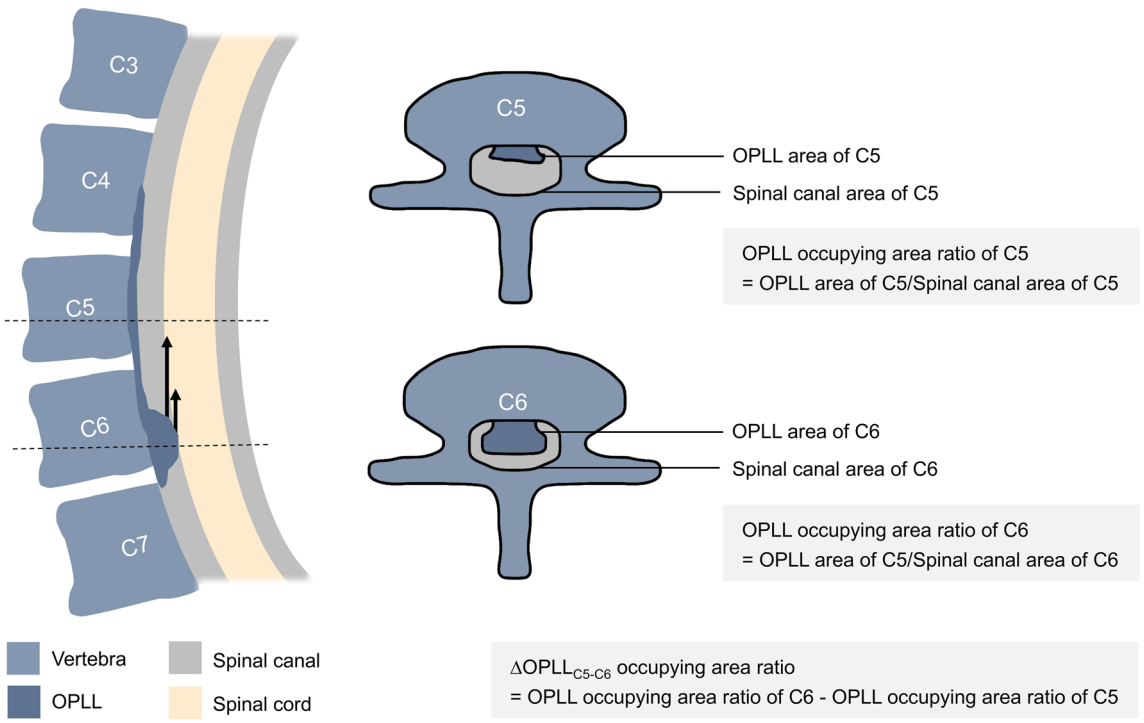

Fig. 1 The measurement of OPLL and the predictive axial loading in spinal cord. Radiological measurements were conducted using the Picture Archiving and Communication System (Centricity PACS, Radiology RA1000 Workstation, GE Healthcare, Barrington, IL, United States). $\Delta OPLL_{C5\text{-}C6}$ occupying area ratio = OPLL occupying area ratio of C6—OPLL occupying area ratio of C5. Given that the apex of the cervical spine in the sagittal plane is typically at C5 or between the C4 and C5 levels, a larger OPLL at the C6 level compared to the C5 level could result in upward axial loading on the spinal cord, especially when the patient extends their neck

*Motor score: The m*otor scores of 10 key muscles were recorded bilaterally according to the International Standards for Neurological Classification of Spinal Cord Injury using the Medical Research Council Scale through manual muscle tests.

Sensory score: Sensory scores were determined using the Japanese Orthopedic Association's (JOA) sensory subscore, which ranged from 0 (obvious impairment) to 2 (normal) for the upper and lower extremities and the trunk, with a maximum score of 6.

Perioperative data

IONM

During surgery, IONM was conducted by a physiatrist and a technician. In total, two physiatrists and two technicians participated in the monitoring process. The Cascade® IONM system (Cadwell Industries Inc., Kennewick, WA, USA) was utilized to continuously monitor intraoperative somatosensory evoked potentials (SEPs) and motor evoked potentials (MEPs) throughout the surgical process.

SEPs: During surgery, bilateral median or tibial nerve SEPs were obtained by stimulating the median nerves at the wrists or the posterior tibial nerves at the ankles (duration, 0.2 ms; repetition rate, 5 Hz), recording at C3 (right median nerve), C4 (left median nerve), and Cz (right and left tibial nerve), and referencing FPz of the international 10–20 electroencephalogram (EEG) system. Baseline waveforms were obtained immediately after electrode placement. Any latency prolongation of > 10% or peak-to-peak amplitude reduction of > 50% from the baseline wave for any monitored nerve was deemed a significant deterioration in SEPs.

MEPs: Transcranial electrical stimulation MEPs were obtained from the bilateral deltoids, abductor pollicis, tibialis anterior, and abductor hallucis muscles. The stimuli consisted of six square-wave pulses (duration, 0.5 ms; interstimulus interval, 5 ms; repetition rate of 2 Hz). The stimulus intensity was incrementally increased, ranging from 250 to 400 mV. The train stimuli were delivered through needle electrodes placed at C3 and C4 according to the international 10–20 EEG system. The interhemispheric montage of C3/C4 and C4/C3 was used to measure MEPs of the right and left extremities, respectively. Baseline waves were obtained by considering the half-life of rocuronium bromide. A reduction in the peak-to-peak amplitude > 50% from the baseline was considered a significant deterioratiopn.

If the alarm thresholds for intraoperative MEPs or SEPs were reached, the surgeon was immediately notified, and any changes in SEP or MEP surpassing the alarm criteria were considered significant, regardless of whether they returned to baseline by the end of the monitoring.

Surgical data

The surgical approach, whether anterior or posterior, was collected. The specific surgical methods, including laminectomy, laminoplasty, anterior corpectomy or anterior discectomy, and the total number of spinal levels operated on were also examined.

Hemodynamic data

The analysis accounted for the total estimated blood loss during surgery and the baseline and minimum values for systolic, diastolic, and mean arterial blood pressures (SBP, DBP, and MAP), along with their respective maximum decreases compared to baseline (ΔSBP, ΔDBP, and ΔMAP).

Anesthesia

Total intravenous anesthesia was delivered with a combination of remifentanil (Ultiva, GSK, Middlesex, UK), propofol (Fresofol, Fresenius Kabi, Seoul, Korea), and occasionally midazolam (Vascam, Hana Pharm, Seoul, Korea). A single dose (50–200 mg) of rocuronium bromide (Esmeron; Han Wha Pharma Co. Ltd., Seoul, Korea) was intravenously administered for intubation. Skin temperature, encompassing the arms and legs, was regulated between 32–36 °C with a warm-air blanket system. Throughout the procedure, vital signs such as body temperature, pulse rate, oxygen saturation, end-tidal carbon dioxide concentration, and direct radial artery pressure were closely monitored.

Postoperative data

The medical records of the neurological examinations, performed by the same physiatrist 48 h after surgery were reviewed. Postoperative motor deterioration (PMD) was defined as any reduction of the motor score of ≥ 1 compared with a preoperative assessment. A sensory score reduction of ≥ 1 compared with the preoperative condition indicated postoperative sensory deterioration (PSD). Patients presenting with either PMD or PSD were classified as having PND and included in the statistical analysis, as both types of deficits can affect functional outcomes.

Statistical and machine learning analysis

Although sensory deterioration is also important, the primary analysis focused on postoperative motor function, as it can be assessed more objectively through physical examination. The baseline characteristics were analyzed using descriptive statistics and frequency analysis. To predict PMD after OPLL surgery, we used ROC curve analysis to

assess the diagnostic accuracy of preoperative and intraoperative variables, including variables related to OPLL size, changes in MEPs, and SEPs. The area under the curve (AUC) was calculated to assess the sensitivity and specificity of the predictors. Additionally, we performed linear path analysis to explore the direct and indirect effects of ΔOPLL occupying area ratios on PMD, mediated by intraoperative MEP or SEP changes. A *p*-value of less than 0.05 was considered statistically significant. These analyses were conducted using SPSS version 23.0 (IBM Corp., Armonk, NY, USA).

Results

Baseline characteristics

Of the 111 patients initially screened, we excluded those without baseline SEP responses (N = 5; 3 for median SEPs, 2 for tibial SEPs), those without MEP responses (N = 4; 2 for abductor pollicis, 2 for tibialis anterior), and those requiring mechanical ventilation with sedatives 48 h after surgery (N = 2). The baseline characteristics of the final 100 patients are summarized in Table 1. The average age was 56.0 years, with a predominance of male patients (M: F = 2.2: 1). Preoperatively, the average value of OPLL AP diameter and the OPLL area at the C2-C7 vertebral levels were 4.1 ± 1.7 (SD) mm and 40.9 ± 23.1 mm^2, respectively. The values of the OPLL occupying AP diameter ratio and the OPLL occupying area ratio were 0.31 ± 0.12% and 0.18 ± 0.16%, respectively. The OPLL longitudinally occupied 4.8 ± 1.2 vertebral levels on average. The APROM was severely limited, measuring 27.4 ± 11.6°. Preoperatively, 67 patients presented with motor deficits and 82 with sensory deficits. The average number of operative level was 4.0 ± 1.1, with the most frequently operated level being C5. The average bleeding amount was 656.5 ± 614.5 mL. During surgery, the SEP and MEP was significantly deteriorated in 14 and 7 patients, respectively. Postoperative motor deterioration (PMD) was examined in 16 patients at 48 h and 11 patients at 4 weeks postoperatively. Postoperative sensory deterioration (PSD) was observed in 11 patients at 48 h and 9 patients at 4 weeks postoperatively.

OPLL occupying diameter and area ratio and intraoperative neurophysiological changes

The OPLL occupying diameter and area ratios were examined in relation to intraoperative neurophysiological changes, including SEP latency, SEP amplitude, and MEP amplitude (Table 2). A significant difference was found only in the OPLL occupying area ratio at the C6 vertebral level concerning significant MEP changes ($P = 0.005$). However, contrary to expectations, the OPLL occupying area ratio was smaller in the MEP change group compared to the non-change group. These results may suggest that axial OPLL size itself is not a significant factor in iatrogenic neural injury, or they may imply that other biomechanical factors play a more critical role than the cross-sectional OPLL size at specific vertebral levels. In addition, there was no significant difference in the number of longitudinal levels occupied by OPLL based on changes in SEP amplitude ($P = 0.845$), SEP latency ($P = 0.274$), MEP amplitude ($P = 0.688$), or the presence of PMD ($P = 0.560$), PSD ($P = 0.730$), or PND ($P = 0.971$) at postoperative 48 h.

Given the longitudinal linearity of OPLL and the limitations in cervical AP motion in the patients, this study also focused on the size differences between adjacent vertebral levels. Biomechanical restrictions can lead to abnormalities in motion; however, due to increased nerve compression from AP motion, it was hypothesized that the axial size discrepancy of OPLL between adjacent levels may have an impact on clinical presentation. Based on the lack of significant differences in the OPLL occupying diameter ratio at any vertebral level with respect to electrophysiological changes (Table 2), the ΔOPLL occupying area ratio was selected as the sole biomechanical parameter for comparison related to EP changes. Table 3 presents the intergroup differences in the ΔOPLL occupying area ratio across two adjacent cervical levels in relation to changes in SEP amplitude, latency, and MEP amplitude. The OPLL occupying area ratio at C5-C6 showed significant differences depending on MEP amplitude reduction (0.21 ± 0.11 in reduction (+) group vs. 0.04 ± 0.14 in reduction (-) group, $P = 0.002$) and SEP latency prolongation (0.06 ± 0.14 in prolongation (-) group vs. −0.07 ± 0.13 in prolongation (+) group, $P = 0.04$).

In addition, regarding PSD, PMD, or PND, no significant differences were observed in the ΔOPLL occupying area ratio at any adjacent cervical levels (Table 3).

Difference in cervical range of motion according to electrophysiologic change

Table 4 describes the differences in cervical range of motion according to significant changes in evoked potentials including SEP amplitude, SEP latency, and MEP amplitude. Considering the range of cervical flexion and extension in asymptomatic adults, this table demonstrate that the patients were more compromized in cervical flexion than extension [15]. There was a significant difference in full flexion between patients with and without SEP amplitude reduction (−10.2 ± 10.7° vs. −0.7 ± 7.6°, $P = 0.003$). However, no significant differences were observed in any C2-C7 Cobb's

Table 1 Baseline characteristics

Variables	Mean (SD) or No.(%)
I. Demographic data	
Age, year, mean (range)	56.0 (9.4)
Sex, No. (%)	
Male	69 (32.1)
Female	31 (14.4)
Height, cm, mean (range)	166.5 (9.5)
II. Preoperative data	
Radiologic data	
OPLL size, mean (SD)	
Axial (average C2-C7)	
OPLL AP diameter, mm	4.1 (1.7)
Spinal canal AP diameter, mm	13.4 (1.1)
OPLL area, mm^2	40.9 (23.1)
Spinal canal area, mm^2	245.7 (26.7)
OPLL occupying AP diameter ratio	0.31 (0.12)
OPLL occupying area ratio	0.18 (0.16)
Max. OPLL occupying AP diameter ratio	0.51 (0.13)
Max. OPLL occupying area ratio	0.31 (0.12)
Longitudinal OPLL occupying level, No	4.8 (1.2)
OPLL type, No. (%)	
Continuous	28 (33.3)
Segmental	22 (26.2)
Mixed	32 (38.1)
Localized	2 (2.4)
Cervical range of motion,°	
Cobb's in full anterior flexion	−9.3 (10.8)
Cobb's in full extension	18.2 (8.2)
APROM	27.4 (11.6)
Neurologic state	
Preoperative motor deficit, No.(%)	67 (67.0)
Preoperative sensory deficit, No.(%)	82 (82.0)
Motor score, mean (SD)	92.9 (7.4)
Sensory score, mean (SD)	4.1 (1.4)
Combined disease, No. (%)	
Hypertension	27 (27.0)
Diabetes mellitus	35 (35.0)
III. Perioperative data	
Surgical data	
Surgical approach, No. (%)	
Anterior approach	26 (26.0)
Posterior approach	74 (74.0)
Surgical method, No. (%)	
Laminectomy	29 (29.0)
Laminoplasty	46 (46.0)
Anterior corpectomy	12 (12.0)
Anterior discectomy	13 (13.0)
Number of operation level, mean (SD)	4.0 (1.1)
Operated spinal level, No. (%)	
C2	32 (8.1)
C3	73 (18.4)
C4	88 (22.2)
C5	91 (22.9)
C6	77 (19.4)
C7	36 (9.1)

Table 1 (continued)

Variables	Mean (SD) or No.(%)
Hemodynamic data, mean (SD)	
Bleeding amount, mL	656.5 (614.5)
Blood pressure, mmHg	
SBP_{base}	141.3 (21.3)
DBP_{base}	80.6 (11.8)
MAP_{base}	100.9 (13.6)
SBP_{min}	87.4 (7.6)
DBP_{min}	47.3 (6.9)
MAP_{min}	60.7 (6.2)
ΔSBP	−53.9 (20.7)
ΔDBP	−33.3 (12.1)
ΔMAP	−40.2 (13.3)
IONM data	
SEPs	
Significant change (+)	14 (14.0)
Significant change (-)	86 (86.0)
MEPs	
Significant change (+)	7 (7.0)
Significant change (-)	93 (93.0)
EPs (SEPs or MEPs)	
Significant change (+)	20 (20.0)
Significant change (-)	80 (80.0)
IV. Postoperative data	
Postoperative neurological deterioration, No.(%)	
PMD_{48hrs}	16 (16.0)
PMD_{4wks}	11 (11.0)
PSD_{48hrs}	11 (11.0)
PSD_{4wks}	9 (9.0)
PND_{48hrs}	23 (23.0)
PND_{4wks}	18 (18.0)
Neurologic state, mean (SD)	
Motor score at postoperative 48 h	91.7 (7.9)
$\Delta Motor_{48hrs}$	−1.2 (4.3)
Motor score at postoperative 4wks	92.0 (11.8)
$\Delta Motor_{4wks}$	−1.0 (10.8)
Sensory score at postoperative 48 h	4.3 (1.4)
$\Delta Sensory_{48hrs}$	+0.3 (0.8)
Sensory score at postoperative 4wks	4.9 (1.3)
$\Delta Sensory_{4wks}$	+0.8 (1.1)

AP, antero-posterior; DBP_{min}, the lowest value of diastolic blood pressure; DBP_{base}, baseline diastolic blood pressure; ΔDBP, DBP_{min} – DBP_{base}; SEPs, intraoperative somatosensory evoked potentials; MEPs, intraoperative motor evoked potentials; IONM, intraoperative neurophysiological monitoring; MAP_{min}, the lowest value of mean arterial pressure; ΔMAP, MAPmin – MAP_{base}; postop., postoperative; Max. OPLL AP diameter OR; maximum OPLL AP diameter OR among C2-C7 vertebral levels; Max. OPLL area OR; maximum OPLL area OR among C2-C7 vertebral levels; OPLL, ossification of posterior longitudinal ligament; PSD_{48hrs}, postoperative sensory deterioration at postoperative 48 h; PSD_{4wks}, PSD at postoperative 4 weeks; PMD_{48hrs}, postoperative motor deterioration at postoperative 48 h; PMD_{4wks}, PMD at postoperative 4 weeks; PND, postoperative neurological deterioration including motor or sensory deterioration; PND_{48hrs}, PND at postoperative 48 h; PND_{4wks}, PMD at postoperative 4 weeks; SBP_{base}, baseline systolic blood pressure; SBP_{min}, the lowest value of systolic blood pressure; ΔSBP, SBP_{min} – SBP_{base}; $\Delta Motor_{48hrs}$, motor score at postoperative 48 h – preoperative motor score; $\Delta Motor_{4wks}$, motor score at postoperative 4 wks – preoperative motor score; $\Delta Sensory_{48hrs}$, sensory score at postoperative 48 h – preoperative sensory score; $\Delta Sensory_{4wks}$, sensory score at postoperative 4 wks – preoperative sensory score

Table 2 OPLL occupying diameter and area ratio by intraoperative neurophysiological changes

Spinal level	ΔOPLL occupying diameter ratio								
	SEP amplitude reduction (-)	SEP amplitude reduction (+)	*P*	SEP latency prolongation (-)	SEP latency prolongation (+)	*P*	MEP amplitude reduction (-)	MEP amplitude reduction (+)	*P*
C2	0.16 (0.18)	0.16 (0.23)	0.951	0.16 (0.18)	0.17 (0.24)	0.875	0.16 (0.18)	0.17 (0.21)	0.854
C3	0.34 (0.21)	0.39 (0.25)	0.498	0.34 (0.21)	0.39 (0.12)	0.612	0.34 (0.21)	0.41 (0.19)	0.404
C4	0.41 (0.18)	0.41 (0.17)	0.966	0.41 (0.17)	0.39 (0.17)	0.635	0.40 (0.18)	0.48 (0.11)	0.244
C5	0.40 (0.17)	0.40 (0.12)	0.989	0.39 (0.17)	0.41 (0.10)	0.777	0.39 (0.17)	0.42 (0.11)	0.633
C6	0.34 (0.18)	0.31 (0.15)	0.702	0.33 (0.17)	0.48 (0.07)	0.058	0.34 (0.18)	0.27(0.07)	0.051
C7	0.23 (0.18)	0.18 (0.21)	0.416	0.22 (0.18)	0.35 (0.23)	0.119	0.23 (0.18)	0.18 (0.16)	0.460
Spinal level	ΔOPLL occupying area ratio								
	SEP amplitude reduction (-)	SEP amplitude reduction (+)	*P*	SEP latency prolongation (-)	SEP latency prolongation (+)	*P*	MEP amplitude reduction (-)	MEP amplitude reduction (+)	*P*
C2	0.08 (0.10)	0.10 (0.15)	0.693	0.08 (0.10)	0.06 (0.10)	0.682	0.08 (0.10)	0.10 (0.13)	0.597
C3	0.19 (0.15)	0.21 (0.19)	0.758	0.19 (0.15)	0.17 (0.10)	0.740	0.19 (0.15)	0.27 (0.15)	0.147
C4	0.24 (0.15)	0.23 (0.18)	0.932	0.24 (0.15)	0.26 (0.20)	0.690	0.23 (0.15)	0.34 (0.15)	0.065
C5	0.23 (0.13)	0.24 (0.16)	0.698	0.23 (0.14)	0.19 (0.11)	0.466	0.22 (0.14)	0.31 (0.12)	0.114
C6	0.18 (0.13)	0.18 (0.15)	0.969	0.17 (0.13)	0.26 (0.70)	0.162	0.18 (0.13)	0.09 (0.06)	0.005*
C7	0.19 (0.76)	0.09 (0.14)	0.685	0.18 (0.74)	0.20 (0.08)	0.929	0.19 (0.75)	0.06 (0.06)	0.672

SEP, Somatosensory evoked potential; MEP, motor evoked potentials; SEP amplitude reduction, > 50% amplitude reduction compared to baseline; SEP latency prolongation, > 10% prolongation compared to baseline; MEP amplitude reduction, > 50% amplitude reduction compared to baseline. *, $P < 0.05$

Table 3 Intergroup differences of OPLL occupying area ratio between adjacent spinal levels according to electrophysiological or clinical outcomes

Adjacent spinal levels	ΔOPLL occupying area ratio								
	SEP amplitude reduction (-) (N = 90)	SEP amplitude reduction (+) (N = 10)	*P*	SEP latency prolongation (-) (N = 95)	SEP latency prolongation (+) (N = 5)	*P*	MEP amplitude reduction (-) (N = 93)	MEP amplitude reducton (+) (N = 7)	*P*
C2-C3	−0.11 (0.11)	−0.10 (0.07)	0.910	−0.11 (0.10)	−0.11 (0.06)	0.973	−0.10 (0.10)	−0.17 (0.16)	0.329
C3-C4	−0.05 (0.11)	−0.03 (0.07)	0.587	−0.04 (0.10)	−0.10 (0.14)	0.272	−0.04 (0.11)	−0.07 (0.07)	0.547
C4-C5	0.01 (0.15)	−0.01 (0.17)	0.663	0.004 (0.15)	−0.08 (0.14)	0.287	0.01 (0.15)	0.03 (0.18)	0.631
C5-C6	0.05 (0.14)	0.07 (0.12)	0.742	0.06 (0.14)	−0.07 (0.13)	0.042*	0.04 (0.14)	0.21 (0.11)	0.002*
C6-C7	−0.01 (0.74)	0.09 (0.16)	0.671	−0.004 (0.72)	0.05 (0.95)	0.868	−0.004 (0.73)	0.03 (0.07)	0.904
Adjacent spinal levels	PSD_{48hrs} (-) (N = 89)	PSD_{48hrs} (+) (N = 11)	*P*	PMD_{48hrs} (-) (N = 84)	PMD_{48hrs} (+) (N = 16)	*P*	PND_{48hrs} (-) (N = 77)	PND_{48hrs} (+) (N = 23)	*P*
C2-C3	−0.11 (0.11)	−0.08 (0.07)	0.272	−0.11 (0.10)	−0.09 (0.09)	0.411	−0.11 (0.11)	−0.09 (0.08)	0.210
C3-C4	−0.05 (0.11)	−0.03 (0.10)	0.491	−0.05 (0.11)	−0.02 (0.08)	0.285	−0.05 (0.11)	−0.04 (0.09)	0.603
C4-C5	0.01 (0.15)	−0.04 (0.18)	0.257	0.02 (0.14)	−0.04 (0.19)	0.136	0.01 (0.14)	−0.02 (0.18)	0.397
C5-C6	0.06 (0.14)	−0.004 (0.16)	0.155	0.06 (0.14)	0.03 (0.14)	0.471	0.06 (0.14)	0.02 (0.15)	0.200
C6-C7	−0.02 (0.74)	0.11 (0.11)	0.574	−0.02 (0.76)	0.12 (0.14)	0.473	−0.03 (0.80)	0.11 (0.13)	0.384
Adjacent spinal levels	PSD_{4wks} (-) (N = 91)	PSD_{4wks} (+) (N = 9)	*P*	PMD_{4wks} (-) (N = 89)	PMD_{4wks} (+) (N = 11)	*P*	PND_{4wks} (-) (N = 72)	PND_{4wks} (+) (N = 18)	*P*
C2-C3	−0.11 (0.10)	−0.08 (0.07)	0.363	−0.11 (0.10)	−0.10 (0.10)	0.846	−0.11 (0.10)	−0.09 (0.09)	0.552
C3-C4	−0.05 (0.11)	−0.03 (0.11)	0.723	−0.05 (0.11)	−0.02 (0.08)	0.418	−0.05 (0.11)	−0.04 (0.09)	0.685
C4-C5	0.01 (0.15)	0.00 (0.16)	0.871	0.01 (0.15)	−0.02 (0.15)	0.492	0.01 (0.15)	0.002 (0.15)	0.877
C5-C6	0.06 (0.14)	−0.01 (0.16)	0.171	0.06 (0.14)	0.02 (0.17)	0.392	0.06 (0.13)	0.01 (0.17)	0.131
C6-C7	−0.01 (0.74)	0.10 (0.12)	0.639	−0.01 (0.74)	0.10 (0.08)	0.609	−0.03 (0.77)	0.11 (0.10)	0.468

ΔOPLL occupying area ratio = OPLL occupying area ratio of upper level – OPLL occupying area ratio of adjacent lower level; SEP, somatosensory evoked potential; MEP, motor evoked potentials; reduction, > 50% amplitude reduction compared to baseline; prolongation, > 10% prolongation compared to baseline; PSD_{48hrs}, postoperative sensory deterioration at postoperative 48 h; PSD_{4wks}, PSD at postoperative 4 weeks; PMD_{48hrs}, postoperative motor deterioration at postoperative 48 h; PMD_{4wks}, PMD at postoperative 4 weeks; PND, postoperative neurological deterioration including motor or sensory deterioration; PND_{48hrs}, PND at postoperative 48 h; PND_{4wks}, PMD at postoperative 4 weeks. *, $P < 0.05$

Table 4 Difference in cervical range of motion according to electrophysiologic change

C2-C7 Cobb's angle	SEP amplitude		*P*	SEP latency		*P*	MEP amplitude		*P*
	Reduction (-)	Reduction (+)		Prolongation (-)	Prolongation (+)		Reduction (-)	Reduction (+)	
Full flexion	10.2 (10.7)	0.7 (7.6)	0.003*	9.3 (10.9)	9.2 (8.3)	0.99	9.8 (10.5)	2.5 (13.3)	0.09
Full extension	17.9 (8.1)	20.4 (9.6)	0.37	18.1 (8.4)	19.3 (5.2)	0.74	18.0 (8.2)	20.0 (9.0)	0.55
APROM	28.1 (11.2)	21.1 (13.6)	0.07	27.4 (11.9)	28.5 (5.3)	0.83	27.8 (11.4)	22.5 (13.8)	0.25

APROM = Cobb's angle of C2-C7 in full posterior extension + Cobb's angle of C2-C7 in full anterior flexion; SEP, somatosensory evoked potential; MEP, motor evoked potentials

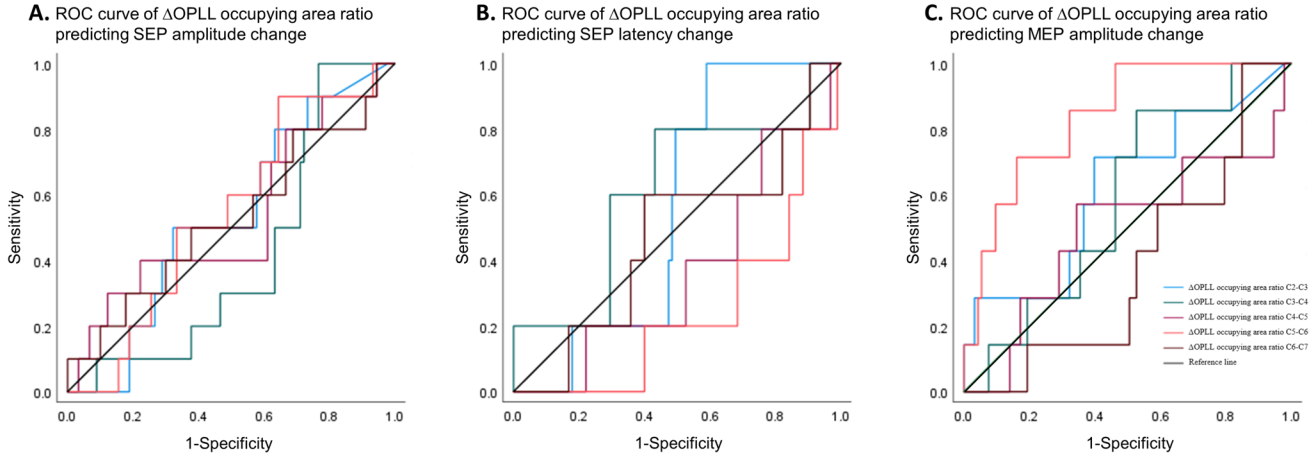

Fig. 2 ROC curve analysis of predictive value of ΔOPLL occupying area ratios for predicting intraoperative neurophysiological changes. ROC curves for ΔOPLL occupying area ratios at different cervical levels (C2-C3, C3-C4, C4-C5, C5-C6, C6-C7) to predict significant intraoperative motor evoked potential (MEP) and sensory evoked potential (SEP) changes. The ΔOPLL occupying area ratio at C5-C6 demonstrates the highest AUC for both MEP and SEP changes, highlighting its critical role as a predictive factor in intraoperative neurophysiological monitoring and subsequent outcomes in OPLL surgery

angle in full flexion, extension or APROM of cervical spine, regardless of changes in SEP latency or MEP amplitude.

ROC curve analysis

ROC analysis was performed to assess the predictive value of the ΔOPLL occupying area ratio at different cervical levels for intraoperative EP changes. The results are shown in Fig. 2 and Table 5. The ΔOPLL occupying area ratio at C5-C6 was statistically significant for predicting MEP amplitude changes, with a high AUC of 0.837 ($P < 0.001$), indicating strong predictive value. However, SEP latency changes at the same level also reached statistical significance ($P = 0.007$) but with a lower AUC of 0.240, suggesting limited predictive strength despite significance. Additionally, at C3-C4, the SEP latency AUC was moderate at 0.615 but did not reach statistical significance ($P = 0.399$), and similarly, at C2-C3, the MEP amplitude AUC was 0.62 but without significance ($P = 0.3$). These findings illustrate varying degrees of predictive utility and statistical significance across cervical levels.

The ΔOPLL occupying area ratio$_{C5–C6}$ demonstrates predictive value for intraoperative neurophysiological changes. For SEP latency prolongation, a cut-off of –0.006 yielded a sensitivity of 68.4% and specificity of 80.0%. In contrast, MEP amplitude reductions were more reliably predicted by a positive ΔOPLL occupying area ratio$_{C5–C6}$, with a cut-off of 0.18 (sensitivity 71.4%, specificity 83.9%).

Linear path analysis

Model fit statistics for the path analysis were evaluated to confirm the adequacy of the proposed structure. The chi-square value (CMIN) was 8.006 with 3 degrees of freedom ($p = 0.046$), and the CMIN/df ratio was 2.669, indicating acceptable fit. The Root Mean Square Residual (RMR) was 0.005, the Goodness-of-Fit Index (GFI) was 0.953, and the Adjusted Goodness-of-Fit Index (AGFI) was 0.907, all supporting good model fit. The Parsimony Goodness-of-Fit Index (PGFI) was 0.477, which is considered reasonable in light of the model's simplicity. The Root Mean Square Error of Approximation (RMSEA) was 0.130, with a 90% confidence interval ranging from 0.016 to 0.243. The p-value for Close Fit (PCLOSE) was 0.091, indicating that the hypothesis of close fit could not be statistically rejected. While the RMSEA point estimate slightly exceeded the conventional threshold, the overall model was considered acceptable,

Table 5 ROC curve analysis for predicting intraoperative neurophysiological changes

ΔOPLL occupying area ratio	ROC curve analysis for predicting SEP amplitude change				ROC curve analysis for predicting SEP latency change				ROC curve analysis for predicting MEP amplitude change			
	AUC	SE	*P*	95% CI	AUC	SE	*P*	95% CI	AUC	SE	*P*	95% CI
C2-C3	0.532	0.083	0.704	0.368—0.695	0.556	0.076	0.466	0.406—0.706	0.62	0.115	0.3	0.393—0.846
C3-C4	0.412	0.076	0.251	0.262—0.562	0.615	0.136	0.399	0.348—0.881	0.587	0.092	0.346	0.406—0.767
C4-C5	0.532	0.103	0.753	0.331—0.733	0.368	0.117	0.260	0.140—0.597	0.495	0.128	0.966	0.244—0.746
C5-C6	0.543	0.083	0.602	0.381—0.706	0.240	0.096	0.007*	0.051—0.429	0.837	0.065	<0.001*	0.711—0.964
C6-C7	0.527	0.104	0.798	0.323—0.731	0.469	0.131	0.816	0.212—0.727	0.384	0.091	0.244	0.205–0.563

AUC, area under curve; CI, confidence interval; MEP, motor evoked potential; OPLL, ossification of posterior longitudinal ligament; ΔOPLL occupying area ratio = OPLL occupying area ratio of upper level – OPLL occupying area ratio of adjacent lower level; ROC, receiver operating characteristic; SE, standard error; SEP, somatosensory evoked potential. *, $P < 0.05$

especially given the limited sample size and degrees of freedom.

Figure 3 presents the results of the linear regression-based path analysis to examine the direct and indirect effects of the ΔOPLL occupying area ratio at C5-C6 on MEP amplitude changes and subsequent PMD. The path analysis revealed that the ΔOPLL occupying area ratio at C5-C6 had a significant indirect effect on PMD through MEP amplitude change. This occurred via a direct effect of the ΔOPLL occupying area ratio at C5-C6 on MEP amplitude change (B = 0.561; $P = 0.002$; β = 0.310; 95% CI, 0.216—0.905), and a direct effect of MEP amplitude change on PMD (B = 0.289; $P = 0.045$; β = 0.201; 95% CI, 0.007—0.571). This suggests that the larger the ΔOPLL occupying area ratio at C5-C6, the more likely significant MEP changes occur, which in turn increase the risk of PMD. However, no direct effect of the ΔOPLL occupying area ratio at C5-C6 on PMD was observed (B = −0.197, $P = 0.454$; β = −0.076; 95% CI, −0.716—0.323), highlighting the mediating role of MEP changes.

Discussion

Recent studies on cervical OPLL have demonstrated that a large axial size of OPLL is associated with poor neurological recovery [16, 17]. Unlike previous studies, we found that the axial size of OPLL had no direct impact on postoperative sensory or motor deterioration, even though the diameter and area of OPLL at each spinal level were analyzed separately. Additionally, the number of longitudinal levels occupied by OPLL did not influence postoperative sensory or motor deterioration. However, we identified that a large ΔOPLL occupying area ratio at the C5-C6 level was a significant risk factor for PMD, along with significantly reduced MEP ampitude. This provides a rationale for explaining surgical risks to patients, particularly emphasizing the necessity of IONM, including MEP, for high-risk patients, such as those with a significant difference in OPLL axial area between the C5 and C6 levels, who may be more prone to postoperative weakness. Moreover, it suggests that continuous monitoring of MEP is essential, as the monitoring professional should alert the surgeon preemptively if the MEP amplitude approaches the alarm criteria, even before a significant reduction occurs.

Biomechanical features

The ΔOPLL occupying area ratio at C5-C6, alongside alterations in cervical biomechanics such as APROM appears to play a crucial role in PMD. Previous studies have shown that the C5-C6 level exhibits the largest APROM in

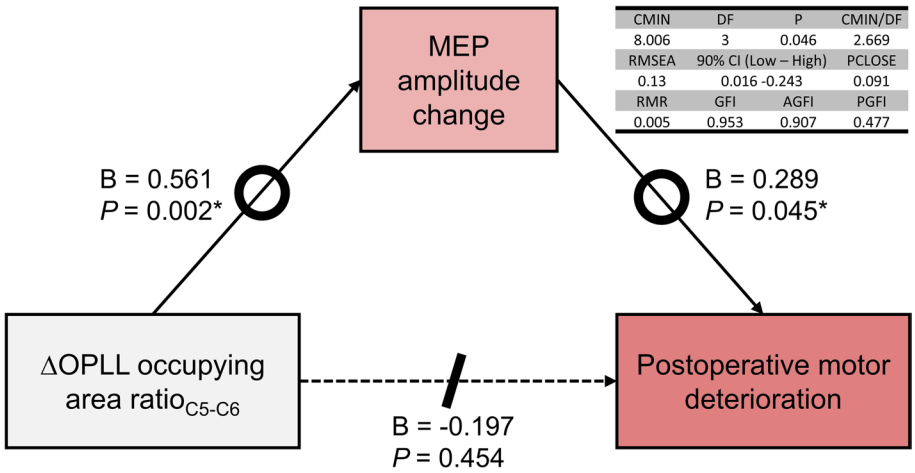

Fig. 3 Path analysis among ΔOPLL occupying area ratio$_{C5\text{-}C6}$, MEP amplitude, SEP latency, and postoperative neurologic deterioration. The path analysis illustrates the relationship between the ΔOPLL occupying area ratio at C5-C6, motor evoked potentials (MEP), and postoperative motor deterioration (PMD). The ΔOPLL occupying area ratio at C5-C6 has a significant indirect effect on PMD through MEP amplitude change. There was a direct effect of ΔOPLL occupying area ratio at C5-C6 on MEP amplitude change (B = 0.561; P = 0.002; β = 0.310; 95% CI, 0.216—0.905), and a direct effect of MEP amplitude change on PMD (B = 0.289; P = 0.045; β = 0.201; 95% CI, 0.007—0.571). However, no direct effect of the ΔOPLL occupying area ratio on PMD was observed (B = −0.197, P = 0.454; β = −0.076; 95% CI, −0.716—0.323), indicating that MEP amplitude change mediate the relationship between the ΔOPLL occupying area ratio at C5-C6 and PMD. CI, confidence interval. *, P < 0.05

physiologically normal adults [18]. In our cohort, all patients had C5 included at the operative level, and a larger OPLL occupying area ratio at C5-C6 was associated with significant changes in both SEP and MEP readings. This suggests that mechanical stress at this level could contribute to PMD development, mediated by neurophysiological changes.

The path analysis further confirmed that the ΔOPLL occupying area ratio at C5-C6 influences PMD indirectly through its effect on MEP changes, without a direct effect on PMD. This underscores the importance of neurophysiological monitoring in predicting outcomes. The biomechanical changes at the C5-C6 level likely exacerbate the vulnerability of the spinal cord and nerve roots, leading to postoperative neurological issues, particularly PMD.

C5 palsy has been identified as a relatively frequent complication following OPLL surgery, with reported incidence rates ranging from 4.8% to 13.2% [19–22]. The increased APROM at C5-C6, combined with the progression of OPLL, likely contributes to neural injury at this level. Unlike previous studies that found APROM to be associated with general postoperative complications, our analysis did not find a direct link between APROM and PMD. Rather, our findings suggest that surgical-induced biomechanical changes and the consequent stress on the neural structures at C5-C6 may be key contributors to PMD.

Patients who present for surgery due to cervical OPLL typically experience progressive neurological symptoms rather than complete paralysis. These symptoms often result not only from the absolute size of the ossified ligament but also from its interaction with cervical spine motion. Particularly, differences in OPLL size between adjacent levels may contribute to dynamic spinal cord stress, as uneven loading during flexion and extension can cause repetitive microtrauma. Anatomically, the C5–C6 level is known to be the most mobile and mechanically burdened segment of the cervical spine, acting as a transitional zone between the relatively fixed upper cervical and more stable lower cervical regions [23]. Its position near the apex of the cervical lordosis also subjects it to frequent compressive forces during daily activities. Given that the apex of the cervical spine in the sagittal plane is typically at or around the C5 level, this region is particularly susceptible to dynamic stress during motion. A relatively larger OPLL at C6 compared to C5 may amplify axial loading and shear stress on the spinal cord, especially during extension (Fig. 1). This may explain why differences in OPLL occupying area at this specific level are more predictive of neurophysiological deterioration. This hypothesis aligns with previous biomechanical studies demonstrating that motion-induced spinal cord deformation is maximal at C5–C6, particularly in patients with preexisting stenosis or mass effect. Therefore, even moderate OPLL growth at this level—or asymmetry between adjacent segments—may disproportionately affect neurological outcomes.

Electrophysiological features

The neurophysiological findings from this study highlight the critical role of intraoperative monitoring in predicting PMD. The ROC analysis demonstrates that the ΔOPLL

occupying area ratio at C5-C6 was the predictor of significant changes in MEP and SEP readings. For SEP latency prolongation, a cut-off of –0.006 yielded a sensitivity of 68.4% and specificity of 80.0%. In contrast, MEP amplitude reductions were more reliably predicted by a positive ΔOPLL occupying area ratio$_{C5–C6}$, with a cut-off of 0.18 (sensitivity 71.4%, specificity 83.9%). Although the model for SEP latency change was statistically significant, the clinical relevance of the –0.006 cut-off remains uncertain. This represents less than a 1% difference between C5 and C6, which may fall within the typical variability of radiologic measurements and limits its practical applicability. Several contextual factors may have contributed to this result, including the predominance of posterior approaches—which can preferentially affect the dorsal column and SEP signals—the inclusion of anterior approaches with lower susceptibility to neurophysiological changes, and the small sample size. In contrast, the cut-off of 0.18 for predicting MEP amplitude reduction appears more clinically meaningful. When the OPLL occupying area ratio at C5 exceeds that at C6 by 0.18 or more, the likelihood of intraoperative MEP deterioration increases. While direct calculation of the ΔOPLL occupying area ratio$_{C5–C6}$ may not be routine in busy clinical practice, this finding may still guide surgical planning. Notably, when preoperative CT imaging shows a visibly larger OPLL mass at C5 than at C6, clinicians may consider intraoperative precautions such as optimizing patient positioning or using gentler decompression techniques to reduce the risk of neurologic injury.

In interpreting the path analysis results, we acknowledge that the limited sample size, particularly the small number of PMD cases, may constrain the statistical power and precision of the model. Notably, Kenny, Kaniskan, and McCoach (2015) have reported that RMSEA tends to be inflated in models with low degrees of freedom and small sample sizes, cautioning against its overinterpretation [24]. In accordance with their recommendation, we assessed multiple fit indices in addition to RMSEA and considered theoretical justification to support the adequacy of our model. Despite the statistical limitations, we believe that the model retains clinical and methodological value, particularly given the rarity of OPLL. As such, we have planned future validations in larger, multicenter cohorts.

Although we conducted segment-specific analyses across cervical levels, no formal correction for multiple comparisons (e.g., Bonferroni method) was applied. This decision was made to avoid an overly conservative threshold that could increase the risk of type II errors in this exploratory study.

Surgical design

Our study did not find a statistically significant difference in the risk of PMD between anterior and posterior surgical approaches, despite previous reports suggesting a higher incidence of complications following posterior surgeries such as laminectomy [25]. Given that the choice of surgical approach depends on the size, location, and extent of the OPLL, the lack of a significant difference in our analysis may be due to variability in patient selection and surgical planning. Further studies with more standardized criteria are needed to evaluate the role of surgical approach in predicting PND.

Limitations

There are several limitations to this study. The retrospective design limits causal interpretation and may introduce unmeasured confounding. Selection bias is also possible, as only patients with IONM and complete follow-up were included. The limitations of this study include its single-center design, relatively small sample size, and the fact that all participants were from an Asian population. Notably, since OPLL has been reported to have a higher prevalence in East Asian countries, the lack of ethnic diversity should be acknowledged as a limitation when interpreting the generalizability of the findings. The small sample size limited our ability to adjust for confounding factors, affecting the reliability and generalizability of the results. OPLL patients exhibit a heterogeneous range of clinical presentations and cervical stenosis, leading to variability in surgical planning and outcomes. Moreover, the imbalance between PMD and non-PMD groups (PMD, N = 16; non-PMD, N = 84) may have introduced bias. To mitigate this, we used ROC curve analysis and linear path analysis to provide robust insights into the predictive factors for PMD and PSD. However, in interpreting the path analysis, we acknowledge that the observed associations are exploratory in nature and do not imply causality. Given the complexity of perioperative and anatomical factors in OPLL, the possibility of residual confounding or unmeasured variables remains. In addition, due to the varying number of OPLL occupying longitudinal levels among patients, individual OPLL occupying longitudinal levels could not be accounted for in the analysis of the OPLL area ratio between two adjacent spinal levels. For instance, in a patient with OPLL present only at the C4-C6 levels, the difference in the OPLL ratio between the C2-C3 levels would necessarily be zero. Furthermore, myotomal correlation between intraoperative MEP changes and postoperative motor deficits could not be fully analyzed, as MEP monitoring was limited to four representative muscles, which may restrict the interpretability of MEP alerts

in relation to level-specific neurological outcomes. Ideally, muscle selection would have been tailored to the key symptomatic levels in each patient, but such individualized monitoring was not feasible in this study. This was not only due to reimbursement constraints, but also to technical limitations of the monitoring system; specifically, the software of the IONM device used in this study allowed only a limited number of MEP recording channels. This limitation was further compounded by the bundled reimbursement model in Korea, which does not provide separate compensation for electrode costs, making it unfeasible to include all segmentally relevant muscles. Inherent limitations in IONM sensitivity and specificity may also affect interpretation. Future multicenter, prospective studies are needed to validate and expand upon these findings.

Conclusion

This study suggests that the ΔOPLL occupying area ratio at C5-C6 may serve as a potential predictor of PMD in cervical OPLL surgery, with its effect possibly mediated by the intraoperative MEP changes. These findings highlight the potential value of incorporating neurophysiological monitoring and targeted biomechanical assessments into surgical planning to help improve patient outcomes.

Author contribution The paper was co-authored by Jinyoung Park (first author), Seungjun Ryu (first author), Myungeun Yoo, Hyo Jeong Lee, Young Seok Kim, Chae Hwan Lim, Seok Young Chung, Dawoon Kim, Yong Eun Cho, and Yoon Ghil Park. Jinyoung Park and Seungjun Ryu equally contributed to this study as primary authors. Yoon Ghil Park contributed to this study as corresponding authors. Jinyoung Park and Seungjun Ryu wrote the main manuscript text. Myungeun Yoo, Hyo Jeong Lee and Young Seok Kim prepared Figs. 1–3. Chae Hwan Lim, Seok Young Chung, Dawoon Kim prepared Table 1–5. Yong Eun Cho and Yoon Ghil Park supervised the project and handled project administration. All authors reviewed the manuscript. *Jinyoung Park and Seungjun Ryu contributed equally as co-first authors. *Yoon Ghil Park and Yong Eun Cho contributed equally as co-corresponding authors.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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