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Preliminary observations on neuromuscular pathways of the lower extremities: findings from intraoperative nerve root stimulation

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ABSTRACT

The segmental innervation patterns of lower extremity muscles remain poorly defined, despite their critical importance in both clinical diagnosis and surgical planning for lumbar spinal conditions. Variability in these patterns, particularly under chronic nerve root compression, complicates the development of accurate diagnostic and therapeutic strategies. This study aimed to elucidate the segmental innervation patterns of lower extremity muscles through intraoperative nerve root stimulation during lumbar spinal surgery combined with motor evoked potential (MEP) during lumbar spinal surgery. A total of 30 patients diagnosed with unilateral nerve root impairment due to degenerative lumbar canal stenosis were enrolled in this study. All patients provided informed consent, demonstrated lower extremity muscle strength graded 4 or higher on the manual muscle test, and were scheduled for surgeries that enabled direct visualization of bilateral nerve roots. During the surgical procedures, 128 lumbosacral nerve roots (L2–S1) were stimulated using a monopolar stimulator, and MEPs were recorded from key lower extremity muscles, including the vastus lateralis, tibialis anterior, and medial gastrocnemius. The vastus lateralis muscle was consistently innervated by the L2 root in 100% of cases, confirming a stable and reproducible pattern. In contrast, stimulation of the L5 root revealed notable anomalies in 8% of cases, where compensatory mechanisms or anatomical anomalies appeared to alter the expected innervation patterns. Furthermore, differences in muscle innervation between the left and right sides were observed in 39% of tested nerve roots, with variability being particularly pronounced in lower lumbar levels, such as L4, L5, and S1.

Keywords: segmental innervation, nerve root stimulation, motor evoked potentials, lumbar spinal surgery, chronic nerve compression

Abbreviations:
MEP: motor evoked potential
TA: anterior tibialis

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INTRODUCTION

The segmental innervation of human muscles, particularly those of the lower extremities, remains an area of ongoing investigation despite extensive clinical and anatomical studies.[1,2] Previous research has demonstrated that lower extremity muscles are innervated by multiple nerve roots from the lumbosacral plexus, with significant interindividual variability. This complexity is often exacerbated by anatomical anomalies such as transitional vertebrae, nerve branching patterns, and degenerative conditions, which complicate the clinical interpretation of symptoms in lumbar spinal disorders.[3-6]

Intraoperative neuromonitoring plays a pivotal role in minimizing the risk of neurological deficits during spinal surgery by providing real-time feedback on nerve function. Among the various techniques available, direct nerve root stimulation combined with motor evoked potentials (MEPs) offers a unique opportunity to accurately map the true innervation patterns of lower extremity muscles.[4,6] Unlike traditional myotomal maps that provide a static view of nerve-muscle relationships, this approach can reveal dynamic and functional changes in innervation, particularly under pathological conditions such as chronic nerve root compression.[3-5]

Recent studies have explored segmental motor innervation in patients with sacral fractures and unilateral nerve injuries, showing that muscles like the gluteus medius, gluteus maximus, extensor digitorum brevis, and abductor hallucis are primarily innervated by specific nerve roots, including L5, S1, and S2-S3.[4,6] However, these findings are largely limited to specific clinical scenarios, leaving significant gaps in understanding how chronic mechanical compression affects nerve function and leads to compensatory shifts in muscle innervation. Addressing this gap is crucial for refining intraoperative neuromonitoring techniques and improving the accuracy of clinical diagnoses and treatment strategies.

This study aimed to elucidate the segmental innervation patterns of lower extremity muscles through intraoperative nerve root stimulation during lumbar spinal surgery. By identifying deviations from traditional myotome maps, this research seeks to enhance understanding of anatomical variability, including both normal innervation patterns and potential compensatory reinnervation mechanisms.

METHODS

Study design and population

This was a study including patients who underwent lumbar spinal surgery at a single spine center. A retrospective analysis was performed to investigate the segmental innervation patterns of the lower extremity muscles via intraoperative nerve root stimulation and MEPs during lumbar spinal surgery. This study was approved by Konan Kosei Hospital Institutional Review Board (IRB). The inclusion criteria included patients who provided informed consent for participation, those with unilateral nerve root impairment due to degenerative lumbar canal stenosis, those with lower extremity muscle strength of manual muscle test grade 4 or higher, and those scheduled for surgery allowing direct visualization of bilateral nerve roots to the foraminal level. Patients with peripheral neuropathy, such as diabetic neuropathy, were excluded from the study.

Procedures

A total of 128 lumbosacral nerve roots, including L2 roots (n = 4), L3 roots (n = 18), L4 roots (n = 50), L5 roots (n = 48), and S1 roots (n = 8), were stimulated. Direct nerve root stimulation was performed using a monopolar stimulator with a platinum head (diameter 2.5 mm), a duration

of 0.2 ms, and a maximum intensity of 0.1–15 mA. Based on previous studies and established guidelines for intraoperative neuromonitoring, a compound muscle action potential amplitude of ≥15 μV sustained for at least three consecutive stimulations was considered a valid response.

Needle electrodes were bilaterally placed on the vastus lateralis (VL), long head of the biceps femoris (BFl), anterior tibialis (TA), and medial gastrocnemius (MG), selected for their representation of different lumbosacral nerve root levels and relevance to lower extremity motor function. MEPs were recorded using needle electromyography (EMG) and the Epoch XP system (Axon Systems).

Total intravenous anesthesia was maintained with propofol (4–6 mg/kg/h) or via Target-Controlled Infusion (TCI) at a target concentration of 2.0–3.5 μg/mL, in combination with fentanyl (0.2 μg/kg/min) or remifentanil (0.1–0.3 μg/kg/min). Neuromuscular blockade was induced with an initial bolus of rocuronium (0.6 mg/kg) to facilitate endotracheal intubation, with no additional doses administered, in order to preserve MEP responses. This anesthesia protocol was chosen to minimize interference with neuromonitoring and ensure accurate evaluation of nerve root stimulation.

Statistical analysis

The frequency of muscle innervation responses across different nerve root levels was compared using Chi-square tests. All statistical analyses were performed using IBM SPSS Statistics version 29.0 (IBM Corp, Armonk, NY, USA). A P-value <0.05 was considered statistically significant.

RESULTS

A total of 30 patients (15 males and 15 females) with an average age of 61 years were included in this study. Among them, 16 patients were diagnosed with degenerative lumbar spondylolisthesis, 7 with degenerative lumbar scoliosis, 4 with lumbar spondylolytic spondylolisthesis, and 3 with other spinal conditions. All patients underwent posterior lumbar interbody fusion (PLIF) with pedicle screws. Single-level PLIF was performed in 20 cases, two-level PLIF in 8 cases, and three-level PLIF in 2 cases.

A total of 128 lumbosacral nerve roots were stimulated during surgery: 4 L2 roots, 18 L3 roots, 50 L4 roots, 48 L5 roots, and 8 S1 roots. The observed innervation patterns revealed notable variability. For instance, the quadriceps muscle was consistently innervated by the L2 root in 100% of stimulations. In contrast, anomalous myotome patterns were identified in 8% of L5 root stimulations, suggesting potential compensatory mechanisms or anatomical anomalies. Additionally, differences in muscle innervation between the left and right sides were observed in 39% of the tested nerve roots, with variability being more prominent in the lower lumbar levels.

For the L2 root, all stimulations (n = 4) resulted in responses in the quadriceps muscle, demonstrating consistent innervation (Figure 1). In the case of the L3 root, 67% of stimulations elicited responses in the quadriceps muscle, either alone or in combination with the hamstrings, indicating moderate variability in innervation patterns (Figure 2). The L4 root showed that 58% of stimulations resulted in responses in the quadriceps, while responses in the tibialis anterior were observed in 28% of cases (Figure 3). Furthermore, differences in muscle activation patterns between the left and right sides were observed in 48% of cases, highlighting significant variability at this level. For the L5 root, the tibialis anterior muscle was activated in 92% of stimulations (Figure 4). However, anomalies were noted, including cases where no response was observed in the TA despite activation of the MG or other muscles, suggesting potential compensatory mechanisms. Finally, for the S1 root, all stimulations (n = 8) produced responses

in the gastrocnemius muscle, and 50% of cases exhibited differences between the left and right sides, indicating the highest variability observed among the tested nerve roots (Figure 5).

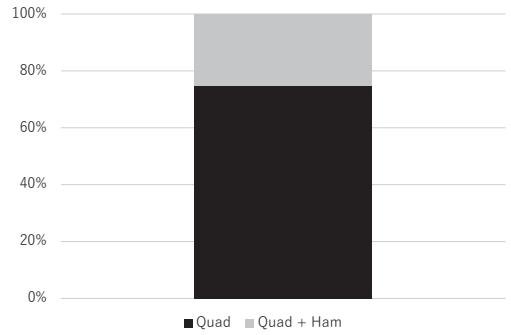

Fig. 1 L2 nerve root stimulation
The results of L2 nerve root stimulation (n = 4) showed that all stimulations resulted in responses in the quadriceps muscle, with specific response rates distributed among the quadriceps alone (Q), quadriceps and hamstrings together (Q + Ham), and hamstrings alone (Ham).

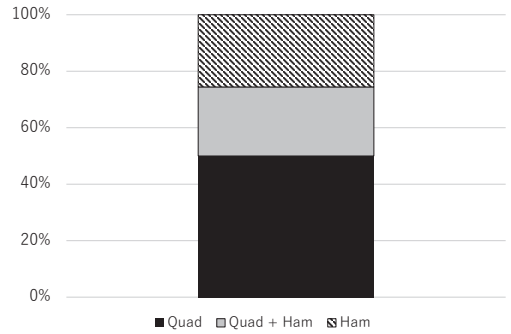

Fig. 2 L3 nerve root stimulation
The results of L3 nerve root stimulation (n = 18) showed that the majority of stimulations (67%) elicited a response in the quadriceps muscle, with specific response rates distributed among the quadriceps alone (Q), quadriceps and hamstrings together (Q + Ham), and hamstrings alone (Ham).

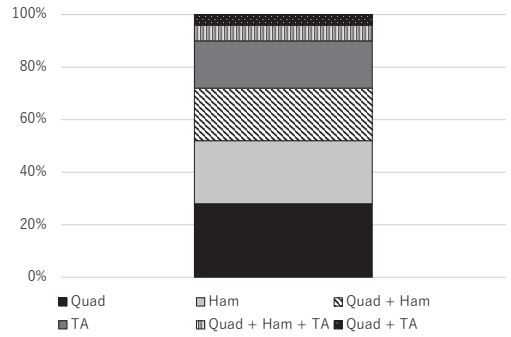

Fig. 3 L4 nerve root stimulation

The results of L4 nerve root stimulation (n = 50) showed that 58% of stimulations elicited a response in the quadriceps muscle, 50% in the hamstrings, and 28% in the tibialis anterior, with specific response rates of 28% for quadriceps alone (Q), 24% for hamstrings alone (Ham), 18% for tibialis anterior alone (TA), 20% for both Q and Ham, 4% for both Q and TA, and 6% for Q, Ham, and TA together.

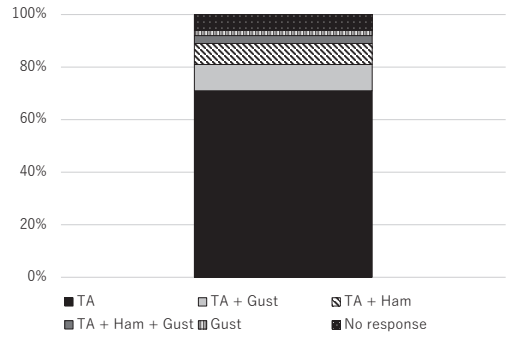

Fig. 4 L5 nerve root stimulation

The results of L5 nerve root stimulation (n = 48) showed that 92% of stimulations elicited a response in the tibialis anterior (TA), with specific response rates of 71% for TA alone, 10% for both TA and gastrocnemius (G), 8% for both TA and hamstrings (Ham), 2.8% for TA, Ham, and G together, and 2% for G alone, whereas 6% showed no response.

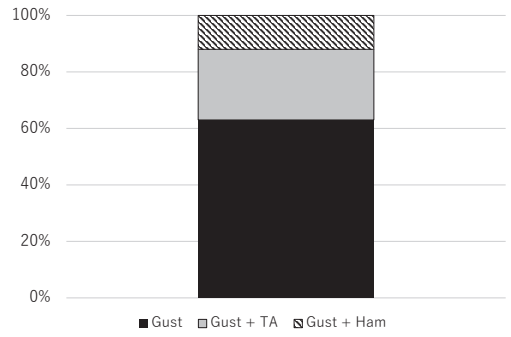

Fig. 5 S1 nerve root stimulation

The results of S1 nerve root stimulation (n = 8) showed that 100% of stimulations elicited a response in the gastrocnemius (G), with specific response rates of 63% for G alone, 25% for both G and tibialis anterior (TA), and 12% for both G and hamstrings (Ham).

Table provides a summary of the observed differences in muscle distribution for each nerve root level. While no left-right differences were observed at the L2 level, variability increased progressively at lower levels, with S1 showing the highest difference rate at 50%. Statistical analysis revealed no significant differences in muscle innervation patterns between nerve root levels ($P = 0.29$). However, the observed variability underscores the complexity of nerve root innervation and the potential influence of compensatory mechanisms or anatomical anomalies.

Table Differences in muscle distribution

Levels	Left-right difference (–)	Left-right difference (+)	Recognized differences (%)
L2	2	0	0%
L3	7	2	22%
L4	13	12	48%
L5	15	9	38%
S1	2	2	50%
Total	39	25	39%

DISCUSSION

This study provides significant insights into the complex and variable nature of lower extremity muscle innervation, particularly under chronic nerve root compression. Using direct intraoperative stimulation of lumbosacral nerve roots and MEPs, we observed notable variability in muscle innervation patterns, especially in lower lumbar levels. These findings underscore the role of anatomical variations, such as nerve branching, in shaping muscle innervation. While previous studies have highlighted variability in myotome patterns, our results extend these observations by exploring dynamic compensatory mechanisms that may emerge under chronic nerve compression.

In our study, 58% of L4 nerve root stimulations elicited responses in the quadriceps, while 92% of L5 stimulations resulted in responses in the TA. These findings are in line with recent studies reporting similar activation rates.[6] This could imply that other nerves contribute to muscle innervation, and understanding these patterns may be important for clinical practice. Improved knowledge of these variable patterns might aid in enhancing the accuracy of intraoperative neuromonitoring, potentially reducing the risk of nerve root injury during lumbar spinal surgery. Furthermore, these insights could be useful in developing personalized postoperative rehabilitation strategies tailored to individual innervation patterns.

Quantifying stimulation thresholds in patients with peripheral neuropathy or chronic nerve root compression proved challenging in this study. Clinical scenarios often reveal discrepancies between symptoms and the affected nerve roots, particularly when transitional vertebrae lead to anatomical abnormalities. Previous research has shown that lumbosacral nerve root innervation can differ from classic myotome maps,[4,6] which might underscore the need for a practical understanding of muscle innervation for accurate EMG responses. The variability we observed suggests that muscle innervation patterns might not always align with textbook descriptions, highlighting the potential value of a more dynamic approach to understanding these patterns in clinical settings.

The variability noted in our L5 nerve root stimulations—where some cases did not elicit responses in the TA while others did in the MG—reflects the complex nature of nerve root in-

nervation. These findings are consistent with recent studies that have reported variability in muscle responses to nerve root stimulation.[6] The absence of a response in the TA does not necessarily indicate L5 nerve root impairment but might suggest a reduction in L5 nerve dominance in this muscle, possibly due to congenital factors or gradual shifts in innervation dominance caused by aging or nerve damage.

In this study, MEPs were considered positive based on criteria established by Lenke et al, where a compound muscle action potential amplitude of 15 μV appearing three consecutive times was deemed a valid response, with most responses occurring at 1–5 mA.[7,8] However, from a neuroprotective perspective, stronger stimulation beyond this threshold was not feasible, particularly in nerve roots compromised by mechanical compression. This limitation raises some uncertainty about whether true muscle innervation patterns can be accurately assessed under such conditions. Given the variability observed in our study and the challenges of assessing nerve function in compromised roots, these results should be interpreted with caution.

This study has several limitations. First, the relatively small sample size and the exclusion of patients with peripheral neuropathy may limit the generalizability of our findings. Second, individual anatomical variations, such as transitional vertebrae and nerve branching patterns, could introduce discrepancies in the data. Third, the criteria and thresholds used to define positive MEP responses may not capture all relevant innervation patterns, particularly in cases of chronic compression. Finally, the limited number of L2 nerve root stimulations (n = 4) was due to the relatively lower incidence of L2 nerve root involvement in lumbar spinal surgeries. While this small sample size limits the generalizability of the results, the observed innervation patterns are consistent with previous studies, providing preliminary insights. Further larger, multi-center studies may be needed to validate these findings and explore the effects of different surgical techniques on nerve root function.

In conclusion, our findings highlight the significant variability and complexity of lower extremity muscle innervation under chronic nerve root compression. This study underscores the importance of personalized approaches to spinal surgery and postoperative rehabilitation, with a focus on understanding individual innervation patterns. Future multi-center studies with larger sample sizes are needed to validate these findings and explore their implications for clinical practice.

CONFLICT OF INTEREST

There are no conflicts of interest, and we have not received any funding for this work.

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