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ORIGINAL ARTICLE

Can triggered electromyography monitoring throughout retraction predict postoperative symptomatic neuropraxia after XLIF? Results from a prospective multicenter trial

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Abstract
Purpose This multicenter study aims to evaluate the utility of triggered electromyography (t-EMG) recorded throughout psoas retraction during lateral transpsoas interbody fusion to predict postoperative changes in motor function.
Methods Three hundred and twenty-three patients undergoing L4–5 minimally invasive lateral interbody fusion from 21 sites were enrolled. Intraoperative data collection included initial t-EMG thresholds in response to posterior retractor blade stimulation and subsequent t-EMG threshold values collected every 5 min throughout retraction. Additional data collection included dimensions/duration of retraction as well as pre-and postoperative lower extremity neurologic exams.
Results Prior to expanding the retractor, the lowestt-EMG threshold was identified posterior to the retractor in 94 % of cases. Postoperatively, 13 (4.5 %) patients had a new motor weakness that was consistent with symptomatic neuropraxia (SN) of lumbar plexus nerves on the approach side. There were no significant differences between patients with or without a corresponding postoperative SN with respect to initial posterior blade reading ($p = 0.600$), or retraction dimensions ($p > 0.05$). Retraction time was significantly longer in those patients with SN vs. those without ($p = 0.031$). Stepwise logistic regression showed a significant positive relationship between the presence of new postoperative SN and total retraction time ($p < 0.001$), as well as change in t-EMG thresholds over time ($p < 0.001$), although false positive rates (increased threshold in patients with no new SN) remained high regardless of the absolute increase in threshold used to define an alarm criteria.
Conclusions Prolonged retraction time and coincident increases in t-EMG thresholds are predictors of declining nerve integrity. Increasing t-EMG thresholds, while predictive of injury, were also observed in a large number of patients without iatrogenic injury, with a greater predictive value in cases with extended duration. In addition to a careful approach with minimal muscle retraction and consistent lumbar plexus directional retraction, the incidence of postoperative motor neuropraxia may be reduced by limiting retraction time and utilizing t-EMG throughout retraction, while understanding that the specificity of this monitoring technique is low during initial retraction and increases with longer retraction duration.

Keywords XLIF · DLIF · EMG · Lumbar plexus · Neuropraxia · Transpsoas approach

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Introduction

The minimally invasive lateral retroperitoneal transpsoas approach provides minimally disruptive access to intervertebral discs, while potentially reducing risk and morbidity that is often associated with direct anterior and traditional posterior approaches [1–3]. However, the lateral approach requires passage of instrumentation through the psoas muscle, avoiding the nerves of the lumbar plexus. In general, lumbar plexus nerves, which originate posteriorly at the foramen, migrate ventral and caudal relative to the lumbar disc spaces from L2 to L5 [4–6]. At the upper lumbar levels, the psoas is not only smaller, but the nerves are typically posterior to the surgical approach, reducing the likelihood of encountering a motor nerve during the transpsoas approach. At the lower lumbar levels, the plexus is denser and the exiting roots conjoin and emanate the main motor branches, specifically L4–L5 and to some extent L3–L4. Given this anatomy, it is not uncommon for nerves to traverse the disc space within a likely approach corridor. Directional dynamically triggered electromyography (t-EMG) with discrete threshold responses mitigates the risk of nerve injury during the approach by indicating both the direction and proximity of a nerve in relation to the approach. This technique is critical to the reproducibility of lateral spine procedures and has been previously described [7–9].

Once successful passage through the psoas muscle has been accomplished and blunt injury to the plexus has been avoided; the plexus may still be at risk of injury secondary to stretch or compression from the posterior retractor blade over the course of retraction. Both animal and human clinical studies have shown that nerve retraction or compression can induce microvascular, structural, and electrophysiological changes [10–16] that are directly correlated with postoperative outcomes such as neurologic deficit and pain [13]. Studies suggest that magnitude and duration of nerve root manipulation are important factors in the incidence and severity of iatrogenic injury and may characterize the potential for recovery [13, 14].

In the current study, it was hypothesized that serial t-EMG recorded via stimulation of the posterior blade of the retractor may effectively monitor the integrity of nerves during the entire course of a minimally invasive lateral interbody fusion (MIS LIF) procedure not just during traversing the psoas muscle. Specifically, that increases in the stimulus intensity required to elicit a muscle EMG response (threshold) over time may potentially indicate a decline in nerve root integrity. The purpose of this study was to evaluate the utility of t-EMG throughout the entirety of MI-LIF to better predict postoperative changes in motor function.

Materials and methods

Patient sample

Patients from 21 treating surgeons undergoing MIS LIF at L4–5, were enrolled in a prospective, institutional review board (IRB)-approved, nonrandomized clinical study. Treatment at spinal levels in addition to L4–5 did not exclude patients from study participation. Patients were excluded from study participation if they had an underlying neurological disease or neurological deficit that was not associated with the condition for which the patient was seeking surgical intervention (e.g., diabetic peripheral neuropathy).

Surgical technique

The MIS LIF (XLIF®, NuVasive Inc., San Diego, CA) approach with integrated directional EMG monitoring and subsequent surgical technique was performed as previously described [7, 17, 18].

Expandable split-blade retractor

The MaXcess® 4 Retractor (NuVasive®, San Diego, CA) consists of three blades (posterior, cranial, and caudal) which can be manipulated for controlled dilation and independent retraction in the cranial/caudal and anterior/posterior directions. Retraction in the cranial/caudal direction is performed by compressing the handles of the retractor which are connected by a sliding crossbar with interlocking teeth. In its closed position, the inside diameter of the cannulation formed by the three blades is 12 mm. As the handles are compressed, the retractor blades are spread apart in the cranial/caudal direction as the interlocking teeth pass over each other, ratcheting the retractor open such that it resists closing with each ratcheting step. Each ratcheting step in the cranial/caudal direction results in approximately 3 mm of additional retraction. Similarly, retraction in the anterior/posterior direction is controlled by a cross bar cylindrical gear that is attached to the handles of the retractor. Turning a knob on the cross bar causes the cylindrical gear to roll along a track, ratcheting the retractor open and increasing the distance between the posterior blade and the cranial/caudal blades by shifting the cranial/caudal blades in the anterior direction. Each ratcheting step in the anterior/posterior direction is equal to approximately 1.5 mm of additional retraction. It should be noted that as retraction increases, pressure is placed against the retractor blades from the surrounding tissue resulting in inward deflection of the retractor blades, such that the actual amount of retraction may be smaller than estimated by the values stated above.

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Triggered EMG

The posterior blade, which includes an exposed electrode at its distal tip, is designed to integrate with the NVM5® (NuVasive Inc., San Diego, CA) neuromonitoring platform to provide directional t-EMG monitoring throughout retraction. At any time during retraction, the surgeon can choose to deliver a measured, constant-current stimulus to the tissue contacting the retractor. The intensity of stimulation required to elicit a measurable response (threshold) and the resulting muscle potential recorded in the corresponding myotome is recorded and displayed by the neuromonitoring software.

Study design

A prospective, multicenter, institutional review board-(IRB) approved study was undertaken in evaluation of the hypothesis. Preoperative data collection included patient demographics and diagnosis. Pre- and postoperative data collection included 0–5 motor and 0–2 sensory function using the modified ASIA exam to evaluate changes in motor and sensory function, and 0–10 patient-reported visual analog scale (VAS) for legs and back. In addition to evaluating motor strength, surgeons also indicated whether motor weakness was a result of neuropraxia during the lateral spine surgery, or more likely to be related to postoperative pain. Intraoperative data collection consisted of procedure details including description, duration of procedure, and blood loss. Additional level-specific data were collected for levels L4–L5 and L3–L4 (if treated) which included the lowest threshold reading and direction (i.e., anterior, posterior, cranial, or caudal) from each of the three dilators during the approach, and the initial t-EMG threshold and direction of the lowest threshold from the retractor's posterior blade after initial expansion. Throughout retraction, posterior blade t-EMG threshold values were recorded every 5 min. Duration of retraction and retraction size, collected in a number of ratcheting steps of the retractor in the anterior/posterior and cranial/caudal directions, were also collected for L4–L5 and L3–L4 levels. Postoperative follow-up visits were conducted 0–2 and 6 weeks after surgery. Patients with new postoperative decreases in motor or sensory function were followed beyond 6 weeks as per each investigator's standard of care. Additional follow-up was scheduled to monitor motor and sensory function until all dermatomes and myotomes had returned to preoperative function, or until the decrease was deemed permanent by the treating surgeon. Any complications that occurred during surgery or within the designated follow-up period were documented.

Statistical analysis

Univariate analysis was performed using Chi squared test and Fishers' exact test for categorical variables and independent samples student t test for continuous variables. A binary multivariate logistic regression was used to identify independent risk factors for new postoperative neuropraxia. Model selection criteria were set as stepwise and variables with $p < 0.10$ were included in the final model. Adjusted odds ratios (aOR) and 95 % confidence intervals were calculated for all variables in the model.

All statistical analyses were performed using JMP software (version 11.1.1 for Windows, SAS Institute Inc., Cary, NC). Statistical significance was defined as $p < 0.05$.

Results

Three hundred and twenty-three patients were enrolled. The mean patient age was 63.2 years (range 30–90) and 67 % were female. The mean Charlson comorbidity index score was 2.4 (range 0–12), and mean BMI was 30.0 kg/m^2 (range 17–50). The majority of procedures (70 %) were performed through a left-sided approach. In addition to treating L4–5, L3–L4 was also treated in 57 % of patients.

Mean retraction time at L4–5 was 23 min (range 6–100). Mean retraction size at L4–5 was 2.9 ratcheting steps (approximately 20.7 mm) in the cranial/caudal direction and 5.5 ratcheting steps (approximately 20.3 mm) in the anterior/posterior direction.

Total blood loss for the lateral procedure, which was inclusive of adjacent levels was estimated to be under 100 cc in 85 % of patients. Mean hospital stay was 3.6 days (range 0–31) inclusive of staged procedures. Eighty-nine percent of patients completed at least one postoperative evaluation. Postoperative changes in motor/sensory function on the approach side included 91 (31 %) patients with new postoperative hip flexion weakness, 38 (13 %) with a new decrease in sensory function, and 13 (4.5 %) with a new motor weakness that was identified by the treating surgeon as symptomatic neuropraxia (SN) on the approach side. Of the 13 patients identified as having symptomatic neuropraxia, weakness often occurred in more than one myotome. In this group, new postoperative weakness was identified in knee extension ($n = 11$), ankle dorsiflexion ($n = 3$), great toe dorsiflexion ($n = 3$), and ankle plantar flexion ($n = 2$). Twelve of the thirteen patients with symptomatic neuropraxia also presented with corresponding hip flexion weakness.

As per the protocol, prior to advancing the retractor over the final dilator, the dilator was rotated through the psoas to identify the direction of the lowest threshold to indicate the direction of the closest nerve with respect to where the

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retractor will be placed. In 70 % of L4–L5 levels treated, the location of the lowest threshold was posterior to the retractor. In the remaining 30 % of patients, the lowest threshold was either equal in all directions (8 %), anterior to the dilator (4 %), or cranial or caudal to the retractor (18 %). Symptomatic neuropraxia occurred in 5 % of patients where the lowest threshold was posterior to the retractor, 0 % of cases where the threshold was equal in all directions, 8 % of cases where the lowest threshold was anterior to the dilator, and 4 % of cases where the lowest threshold was in the cranial or caudal direction.

Retraction time was significantly longer in those patients with SN versus those without (32.3 vs. 22.6 min, $p = 0.031$). There were no significant differences between patients with or without postoperative corresponding SN with respect to the initial posterior blade threshold stimulation (with SN: 14 mA, without SN: 12.8 mA, $p = 0.600$), retraction size in the cranial/caudal direction (with SN: 3.1 ratcheting steps, without SN: 2.8 ratcheting steps, $p = 0.551$), or retraction size in the anterior/posterior direction (with SN: 6.4 ratcheting steps, without SN: 5.5 ratcheting steps, $p = 0.419$) (Table 1).

For the purpose of this analysis, it was assumed that a threshold increase of at least 1 mA may be indicative of a change in the patient's nerve function. Of the 13 patients with SN on the approach side during the postoperative period, 10 had a stimulation threshold increase of at least 1 mA compared to the initial stimulation threshold throughout L4–L5 retraction (true positive). The remaining three patients had no increase in stimulation threshold (false negative). Of the 252 patients who did not experience SN on the approach side during the postoperative period, the stimulation threshold did not increase above the initial threshold throughout retraction in 119 (true negative). In the remaining 133 patients with threshold readings who did not experience postoperative SN on the approach side, the stimulation threshold increased at least one 1 mA above the initial stimulation threshold during L4–L5 retraction (false positive). Using the following sensitivity equation: true positive/(true positive + false negative), the sensitivity of this method of nerve monitoring is 77 %. Using the following specificity equation: true negative/(true negative + false positive), the specificity of this method of nerve monitoring is 47 %. When the same analysis was repeated assuming a 2 mA increase was indicative of a change in nerve function, the sensitivity and specificity of this technique were 77 and 56 %, respectively. When the same analysis was repeated assuming a 3 mA increase was indicative of a change in nerve function, the sensitivity and specificity of this technique were 62 and 64 % respectively (Table 2).

Multivariate analysis showed a significant positive relationship between the presence of SN and total retraction time ($p < 0.001$), change in posterior blade t-EMG threshold over time ($p < 0.001$), and smoking ($p < 0.003$). There was a significant negative relationship between the presence of SN and age ($p < 0.001$), and BMI ($p < 0.001$) (Tables 3, 4). Figure 1 depicts the relationship between the change in initial posterior blade t-EMG threshold over time between patients with and without a corresponding postoperative motor deficit.

Age, BMI, smoking, initial L4–L5 posterior blade stimulation threshold, L4–L5 retraction size, and L4–L5 retraction time, were not significantly different between patients who experienced a postoperative decrease in sensory function and those who did not ($p > 0.05$). Postoperative decreases in sensory function occurred more commonly in females than males (16 vs. 7 %, $p = 0.023$).

Discussion

The reported rate of postoperative lower extremity motor weakness, exclusive of hip flexion, after lateral interbody fusion ranges from 0 to 9.3 % [19–21], with approach-related dysesthesia ranging from 1 to 75 % [22–24]. It is important to note that the wide range of motor and sensory outcomes has been derived from multiple MI-LIF

Table 1 Univariate analysis of intraoperative risk factors for postoperative symptomatic neuropraxia

Risk factor	SN ($n = 13$)	No SN ($n = 310$)	Unadjusted OR	95 % Confidence interval	*P* value
Age	55.3	63.5	1.069	1.017–1.124	
Sex	76 % female	66 % female	1.722	0.512–7.817	0.398
BMI	29.5	30.0	1.012	0.932–1.110	0.784
Tobacco use					
Retraction time (min)	32.3	22.6	0.962	0.926–0.999	0.044
Initial threshold stimulation (mA)	14	12.8	0.976	1.037–1.024	0.427
Retraction size (ratcheting steps)					
Cranial/caudal	3.1	2.8	1.112	0.742–2.034	0.628
Anterior/posterior	6.4	5.5	0.978	0.818–1.204	0.823

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Table 2 Sensitivity (Sen), specificity (Spec), and true and false positive and negative results for various changes in t-EMG thresholds as an 'alarm criteria' for symptomatic neuropraxia

"Alarm criteria" threshold change (mA)	False positive		True negative		True positive		False negative		Sen (%)	Spec (%)
	n	% of positives	*n*	% of negatives (negative predictive value)	*n*	% of positives (positive predictive value)	*n*	% of negatives		
1	133	93.0	119	97.5	10	7.0	3	2.5	77	47
2	111	91.7	140	97.9	10	8.3	3	2.1	77	56
3	92	92.0	160	97.0	8	8.0	5	3.0	62	63
4	84	91.3	168	97.1	8	8.7	5	2.9	62	67
5	77	91.7	175	96.7	7	8.3	6	3.3	54	69
6	69	90.8	183	96.8	7	9.2	6	3.2	54	73

As the change in threshold for the alarm criteria increases from 1 to 6 mA, the number of false positives is reduced by nearly half; however, over the same period the false negative rate increases, meaning that patients with symptomatic neuropraxia would go unidentified if higher thresholds were used

Table 3 Nominal logistic regression parameter estimates

Term	Estimate	*P*
Parameter estimates		
Intercept	−1.611	0.047
Time elapsed	−0.040	<0.001
Threshold change from baseline	−0.049	<0.001
BMI	0.061	<0.001
Age	0.050	<0.001
Smoker (no)	0.370	0.003

techniques. The results of this study specifically evaluate the results of the XLIF procedure with integrated, advanced neuromonitoring. Lumbar plexus nerve complications are generally caused by direct interaction of the nerve with instrumentation or indirect ischemic injury, caused by either stretching or compressing the nerve over time. In this study, once properly positioned, retractor time within the psoas was the most predictive factor for determining neurologic injury. Increasing t-EMG thresholds during retraction indicating declining function is a highly compelling and traceable finding with a sensitivity of almost 80 %. The resiliency of neural elements, though, does not mandate that the person will develop a postoperative deficit. Interestingly, smokers, whose microvascular supply is compromised, were found to be more at risk for developing deficits. Based on the results of this study and prior experience [25–27], the authors believe that neurologic injury can be minimized if specific attention is given to the neural anatomy of the psoas in relationship to the approach trajectory, monitoring t-EMG thresholds throughout retraction, while limiting retraction time and magnitude.

With the exception of the genitofemoral nerve, which is typically on the far anterior aspect of the psoas, plexus nerves from L2–L5 are generally located in the posterior 50 % of the psoas or outside of the muscle [5]. In most cases, the preferred technique is to target the disc between the middle and posterior third of the lateral disc space with the direction of the lowest EMG stimulation threshold during transpsoas passage posterior to the approach. In 70 % of L4–L5 levels treated in this series, the retractor was positioned such that the lowest threshold readings were located posterior to the retractor. This trajectory is advantageous because it positions the retractor anterior to the majority of neural structures and maximizes coverage of the implant–endplate interface across the load-bearing column of the anterior spine, on the border between the posterior thirds of the disc space. Once the posterior blade is in position and secure using an intradiscal shim, it remains stationary and the other two blades retract away from the posterior blade, protecting neural structures from

Table 4 Multivariate analysis of risk factors for postoperative symptomatic neuropraxia

Risk factor	Adjusted OR	95 % Confidence interval	*P* value
Retraction time	0.9667	0.952–0.982	<0.001
Change in posterior blade reading	0.972	0.949–0.995	0.018
Tobacco use	0.407	0.275–0.609	<0.001
Protective factors			
Age	1.050	1.032–1.067	<0.001
BMI	1.048	1.018–1.079	0.001

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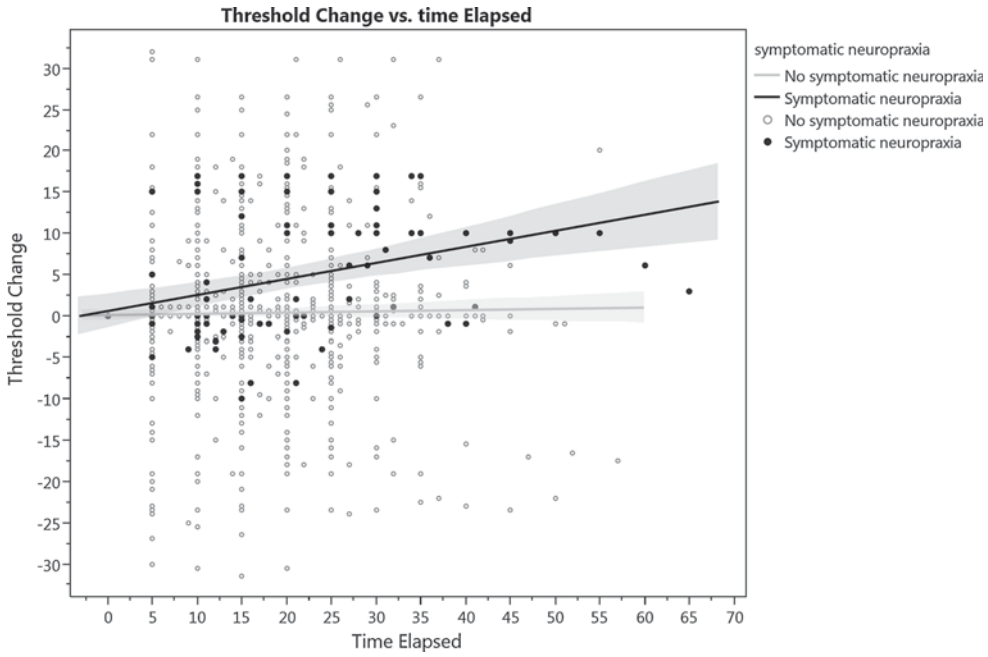

Fig. 1 Change from initial posterior blade electrode stimulation required to elicit a response over time for patients with (*black*) and without (*gray*) symptomatic neuropraxia

additional compression or stretching by the retractor. This positioning also places the posterior blade electrode in close proximity to neural structures allowing for continued and frequent t-EMG monitoring during retraction. In general, investigators in this study limited retraction to relatively small apertures; in 90 % of cases, in patients with and without neuropraxia, L4–L5 anterior retraction was less than 27 mm, and cranial caudal retraction was less than 24 mm. Although comparison of the retraction dimensions in patients with and without symptomatic neuropraxia in this study does not imply that retraction aperture is directly related to postoperative neuropraxia, the authors caution that wide retractor openings are not recommended and may result in neurologic injury and unnecessary trauma to the psoas.

One of the most valuable reasons to monitor changes in t-EMG thresholds would be to allow for early intervention by the surgical team to prevent impending nerve injury. Justification for intervention is predicated on the sensitivity and specificity of the neurophysiological measure being utilized. This being said, despite calculating sensitivity and specificity with increasingly higher threshold change as our assumed 'alarm criteria' for nerve compromise (1–6 mA), these values produced a positive rate that was too high to justify surgical intervention based on any increase in threshold at least in the early stages of retraction (e.g., in the first 20 min). In an attempt to identify whether or not the changes in threshold became more meaningful as the total retraction time increased, we repeated the analysis of looking for an 'alarm criteria' only for readings occurring after 20, 25, 30, and 35 min of retraction. We found that when change in t-EMG threshold was evaluated later in the retraction period (at the 30 min mark), there was an obvious trend for decreasing false positives. While encouraging, the false positive rate remained above 50 % for alarm criteria between 1 and 6 mA. Taken together, these analyses reveal that using change in t-EMG threshold alone as a means to modify surgical technique has very low specificity, i.e., a high false positive rate. Length of retraction time is a clear indicator of nerve injury in the XLIF procedure and interestingly, increases in t-EMG thresholds later during the retraction period may be the only reasonable alarm for surgical intervention. The results of this study illustrate the importance of mixed multimodality neurophysiological monitoring. The majority of nerves within the lumbar plexus are mixed nerves containing both motor and sensory fibers. As such one may have expected to see a relationship between the t-EMG monitoring of motor nerves and the outcomes of sensory function, even in the absence of a motor injury. However, the results of this study do not indicate that monitoring motor nerves can predict the outcome of sensory function.

It should be noted that one of the limitations of the results presented is that if a response was not observed at 30 mA, stimulation was not increased; therefore, discrete threshold measures were only measured up to 30 mA at most institutions. As a result, the stepwise logistic model created to describe the relationship between change in t-EMG threshold and likelihood of a postoperative symptomatic neuropraxia is a limited model, and the increase in threshold in those patients with symptomatic neuropraxia may be greater than what is described by this model. Limitations of the monitoring technique used include an

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inability to monitor the nerves of the psoas muscle because of the inability to place surface electrodes on the corresponding muscle group as well as the inability to directly monitor a specific nerve within the lumbar plexus. Rather than monitoring each nerve individually, stimulation responses are monitored across all myotomes of the lower extremities. Using this technique, if multiple myotomes are stimulated by the electrode, it is possible that a healthy myotome could continue to respond to the t-EMG stimulus while a compromised nerve was failing to respond. Future studies on this topic must aim to directly monitor changes in response to the stimulated thresholds at each myotome, rather than the entire lower extremity. The low specificity of the t-EMG measures in this study may be explained secondary to precisely where the stimulus is being delivered with reference to where the nerve is potentially being compromised. Using this technique, the stimulus is delivered at the site of suspected perturbation potentially creating a degree of variability in threshold recordings. Future studies evaluating the response to stimulation delivered above the surgical site may eliminate the variability of these results.

The results of this study provide evidence that prolonged retraction time is a predictor of declining nerve integrity. While increasing t-EMG thresholds can indicate nerve root compromise, its low specificity raises question concerning its routine utility with regards to surgical intervention during the early stages of retraction. In addition to a careful approach using directional discrete-threshold t-EMG, limiting retraction time and monitoring t-EMG for increasing thresholds, particularly during extended retraction times, may prove effective for reducing the incidence of postoperative motor neuropraxia.

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Conflict of interest Authors JSU, REI, JAY, KK, ASK, FAK, and MDP are consultants to NuVasive. JSU, REI, JAY, KK, and MDP receive research support from NuVasive. JSU and MDP hold shares of NuVasive stock, JSU, REI, JAY, and MDP receive royalties from NuVasive, FAK has been reimbursed for travel on behalf of NuVasive, and MDP is a member of a surgeon advisory board for NuVasive. Author JRB has no conflicts to report.

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