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ORIGINAL RESEARCH

Intraoperative neuromonitoring of anterior root muscle response during hip surgery under spinal anesthesia

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Abstract
The aim of this study was to evaluate the anterior root muscle (ARM) response monitorability during total hip arthroplasty (THA) under spinal anesthesia. A total of 20 adults (64.6 ± 13.87 years old) were monitored using ARM response and free-run electromyography during THA. To elicit the ARM response from muscles, percutaneous stimulation of the lumbosacral roots was performed by self-adhesive electrodes placed over the skin of the projection of the first and third lumbar interspinous space (anode) and over the abdominal skin of the umbilicus (cathode). Latency and amplitude values of the ARM response were recorded from both sides (non-operated and operated) and from five muscles as follows: rectus femoris (RF), vastus lateralis (VL), biceps femoris long-head (BF), Tibialis Anterior (TA) and gastrocnemius. The most recorded ARM response in a muscle was the TA (n = 38); the least recorded AMR response in a muscle was the BF (n = 33). The mean stimulus intensities for the non-operated and the operated sides were 462.5 ± 112.8 V and 520.0 ± 172.3 V (p = 0.834), respectively. The mean latencies and amplitude values of the ARM response from muscles were as follows: 8.8 ± 1.4 ms; 98.8 ± 114.5 µV for RF; 9.8 ± 2.1 ms; 119.1 ± 122.23 µV for VL; 9.5 ± 1.6 ms; 39.6 ± 30.3 µV for BF; 15.1 ± 1.9 ms; 146.6 ± 150.9 µV for TA; 15.6 ± 2.4 ms; 81.0 ± 99.9 µV for Gastrocnemius. The present study demonstrates that the ARM response could easily and safely be obtained during THA under spinal anesthesia. This non-invasive technique may have a potential to detect early neurological deficit in patients who need complex hip surgery under spinal anesthesia.

Keywords Anterior root muscle response · ARM response · Free-run electromyography · Total hip arthroplasty · THA · Intraoperative monitoring

1 Introduction

The two possible physiological mechanisms for generating compound muscle action potential (CMAP) by transabdominal electrical stimulation have been proposed as follows: H-reflex-like activation [1–3] or direct efferent motor root activation [4]. In general, lower voltages may favor an

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H-reflex-like activation, whereas higher voltages endorse efferent motor root activation.

Posterior root muscle (PRM) reflex is elicited by epidural stimulation of posterior lumbar cord structures [5–7]. Monosynaptic PRM reflexes involve the same type of neurons as H reflex; however, the H reflex is evoked by stimulating large-diameter afferents in the peripheral nerves, and a PRM reflex is elicited by stimulating the same sensory axons at proximal sites adjacent to the spinal cord.

A single electrical shock of high intensity, delivered by means of a dorsoventral montage at the proper vertebral level, can safely obtain the synchronous, bilateral and maximal activation of lumbosacral roots very close to their origin in the spinal cord and these can be recorded from muscles as CMAP [2, 8, 9]. Troni et al. described this technique for the first time in 1996 [2]. High-voltage electrical stimulation (HVES) was performed using a trans-abdominal stimulating montage. A silver–silver chloride surface cup electrode (diameter 1 cm) and a large round electrode (diameter 8 cm) were used as a cathode and an anode. The cathode was placed at midline along the vertebral column and the anode was placed midway between umbilicus and the apex of the xiphoid process. Recordings were made from muscles of lower extremities. Authors reported a methodological reappraisal of noninvasive HVES of lumbosacral roots in 2011 [8]. They suggested that maximal activation of lumbosacral roots at their origin is the essential requirement for direct detection of proximal nerve conduction slowing and block in lower limbs. Last, Troni et al. showed for the first time using of HVES as a monitoring tool of nerve function in lumbosacral surgery [9]. CMAPs evoked by HVES were successfully recorded in 20 patients who received general anesthesia throughout the operation from L3 to S2 radicular territories. In 4 patients acute, focal and reversible conduction block was determined using this method intraoperatively. This technique was described as a sensitive tool to early detect conduction failure in manipulated lumbosacral motor roots during an operation. In addition to, the PRM reflex intraoperatively have been used in two studies so far [10, 11]. First, Climent et al. evaluated 30 patients who underwent hip surgery using transcranial motor evoked potential (TcMEP), somatosensory evoked potential (SEP), PRM reflex and anterior root muscle (ARM) reflex [10]. ARM reflex is not clearly described in their poster but might be a response to anterior root stimulation. The study concludes that using multimodal intraoperative monitoring (IOM) modalities in patients who undergo total hip arthroplasty (THA) provides an opportunity to identify the injury in real time and would give patients a chance to avoid permanent postoperative neurological deficit. PRM and ARM reflexes are defined in the study as new intraoperative techniques to evaluate the functional integrity of the lumbosacral plexus and peripheral nerves. The authors suggest that these new methods have good potential and could give more specific information than TcMEP and SEP could. However, no data for PRM reflex and ARM reflex have so far been collected in hip surgery. Second, Mandeville et al. published a case report which describes how the authors had successfully used PRM reflex and TcMEP to monitor the decompression of the sciatic nerve [11]. This case report demonstrates that using the PRM reflex during peripheral nerve surgery as an adjunct to transcranial TcMEP is possible.

Multimodal IOM has been widely utilized in attempt to minimize neurological damage during spine and brain surgeries. However, IOM during hip surgery/arthroscopy to evaluate the function of the nerves has been reported in only a few studies so far [10, 12–15], which general anesthetic regime were used in all of them. However, studies of the effect of anesthetic technique (general versus spinal anesthesia) in hip or knee arthroplasty have shown a close association between spinal anesthesia and lower 30-day mortality, as well as a shorter length of stay in hospital, a reduction in deep surgical site infection rates and reduced rates of postoperative cardiovascular and pulmonary complications [16, 17]. Furthermore, total hip arthroplasty (THA) has been used increasingly often over the last 2–3 decades because of the ageing of the population and increased longevity [18].

IOM during hip surgery has not been used and tested under spinal anesthesia so far. Local anesthetics placed in the subarachnoid space will effectively block sensory, autonomic and motor impulses by interacting with anterior/posterior spinal nerve roots and the dorsal root ganglion. Evidently spinal anesthesia causes dense sensory and motor block. The aim of this study was to evaluate the ability to monitor lumbosacral roots' integrity during hip surgery under spinal anesthesia. HVES was applied to evoke CMAPSs defined as ARM response in our study.

2 Method

2.1 Subjects

A total of 20 adults (13 females, 7 males) who had undergone elective unilateral THA (14 right- and 6 left-sided) using ARM response and free-run EMG were monitored. Our exclusion criteria were as follows: (1) patients who needed acetabular reconstruction for dysplasia and those undergoing revision arthroplasty; (2) patients with a heart arrhythmia, a pace maker or other in-dwelling metallic devices; (3) patients with moderate to severe polyneuropathy; (4) patients with stroke; (5) patients who needed bilateral THA.

The study received approval by the Ethics Committee of our institution. All of the participants gave their informed consent to participate to the study.

2.2 Anesthesia

Spinal anesthesia was performed with patient in sitting position using a 26-gauge pencil point spinal needle in the L3–L4 intervertebral space. All patients received a standard spinal anesthetic consist of 15 mg of % 0.5 bupivacaine and 20 µg fentanyl. After positioning, the patients were sedated with a bolus dose of 2–3 mg midazolam, followed by continuous infusion at 30 µg/kg/h propofol.

To assessment of block height following the administration of spinal anesthesia, the anesthetist tested to cold, pinprick and touch sensations of the patient on the both sides. Ice in a surgical glove was used to evaluate cold sensation. Pinprick and light touch sensations were assessed using 18-gauge needle and a wisp of cotton, respectively. Motor block was evaluated with a modified Bromage Score [19]. After the block heights for each modality were evaluated, the anesthetist considered that the patient had a satisfactory spinal anesthesia block for a hip surgery to proceed.

2.3 Stimulation and recording setup for ARM response and free-run EMG

The IOM was performed during the surgical procedure by dedicated neurophysiologists. The IOM was conducted with the use of a 32 channel device, the Cadwell Cascade Elite (Cadwell Industries, Kennewick, WA, USA). To elicit the ARM response from muscles, percutaneous stimulation of the lumbosacral roots was performed by self-adhesive electrodes placed over the skin of the projection of the first and third lumbar interspinous space (anode) and over the abdominal skin of the umbilicus (cathode) (Fig. 1). A paired stimulus of identical parameters was used with an interstimulus interval (ISI) of 50 ms and duration of 0.5–1 ms. Subdermal needle electrodes (12 mm × 27-gauge) were used for all recordings and placed into the muscles. The ARM response was filtered at high and low cut frequencies of 2000 Hz and 50 Hz, respectively and displayed at 10 ms per division.

Latency and amplitude values of the ARM response were recorded from both sides (non-operated and operated) and from five muscles as follows: rectus femoris (RF), vastus lateralis (VL), biceps femoris long-head (BF), TA and gastrocnemius (GC) (Figs. 2, 3). The minimum stimulus intensity to elicit as much as possible of the ARM response from all muscles was deployed. A favorable ARM response was expected to have a minimum of 50 µV in amplitude in at least one muscle of each nerve distribution (sciatic/femoral). Therefore, we started to stimulate at a very low threshold (50 V) and went up in 25 V steps until we found a recordable ARM response. We continued to stimulate the patient to the threshold that could elicit the maximum number of ARM response with the minimum of leg movement. At its highest, the stimulus intensity was increased to 1000 V.

Free-run EMG was used to monitor for the presence of neurotonic activity, which signals potential harm to spinal nerve roots or spinal nerves. The above-mentioned muscles were used for the recording. The continuous monitoring of the free-run EMG was filtered at high and low cut frequencies of 100 Hz and 5000 Hz, respectively and displayed at 10 ms per division.

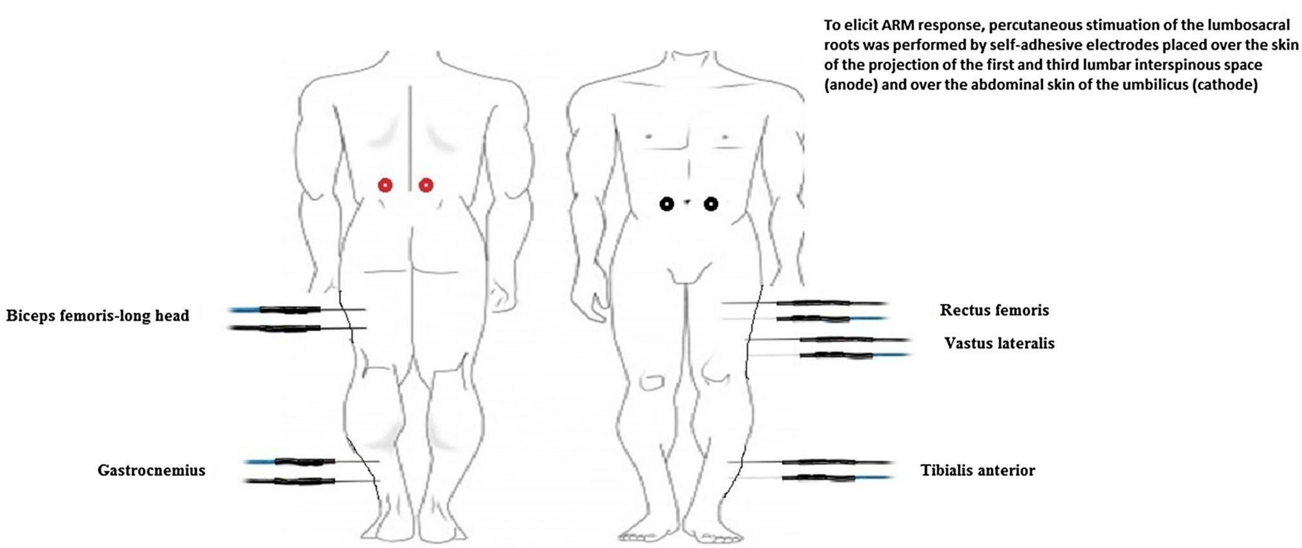

Fig. 1 Methodology for anterior root muscle response recordings

Fig. 2 Intraoperative monitoring screen is shown for recordings. Free-run EMG is located at the left side on the screen. The of ARM response from muscles of the patient' right and left sides are seen at the right and the middle parts of the screen. The muscles from the top down are rectus femoris (RF), vastus lateralis (VL), biceps femoris long-head (BF), tibialis anterior (TA) and gastrocnemius (GC). Markers for latency and amplitude values of gastrocnemius muscles are shown

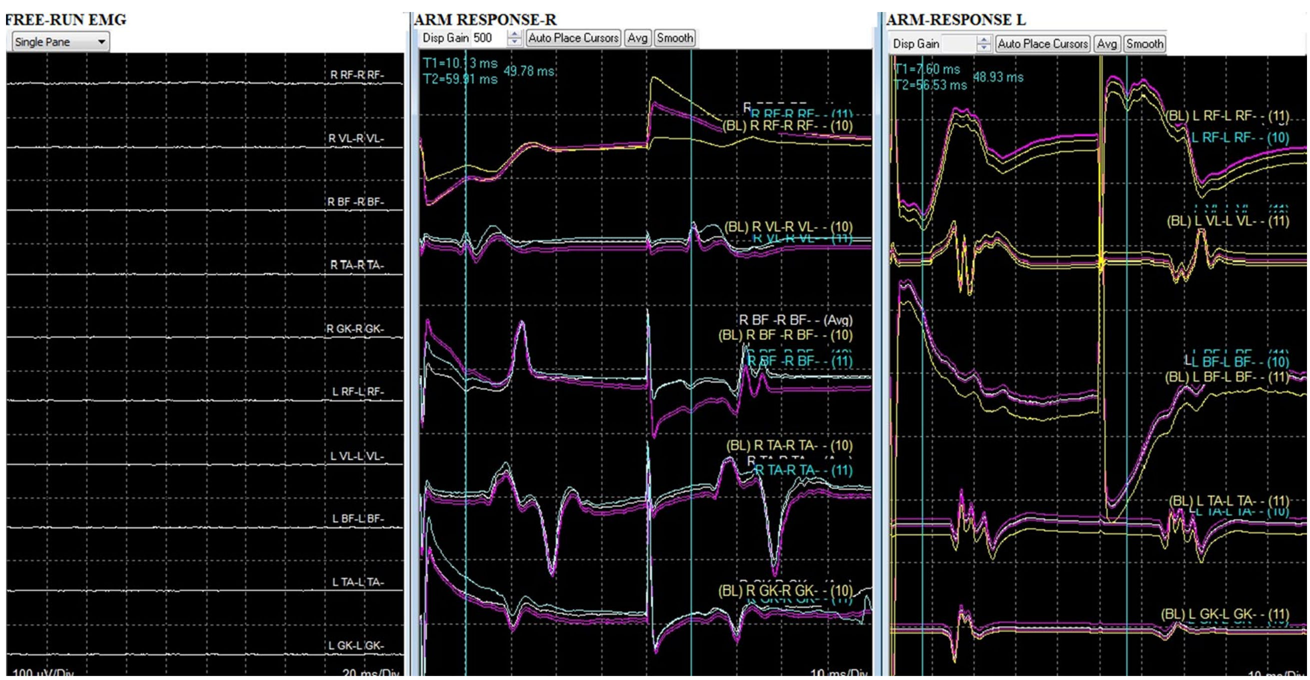

Fig. 3 Intraoperative monitoring screen is shown for recordings as follows; free-run EMG, the right and the left sides of the ARM response

2.4 Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) Version 23.00. The data of continuous variables were presented as mean, median and standard deviations (SDs). A Chi square test was used to compare the stimulus intensities between the non-operated and operated sides. A comparison of variables between the groups was performed using the two independent related samples test. Spearman rank correlation (rho) was used to evaluate the correlation between the variables. In the analyses, all p values below 0.05 were considered significant.

3 Results

Table 1 shows the demographic features of the subjects, the number of recorded ARM response from muscles and the mean stimulus intensity for the non-operated side and the operated side.

All the ARM response of muscles for both the non-operated and operated sides were successfully recorded from 11 patients (55%). We record no ARM response on the operated side in only one patient (Patient 15) (5%). The mean number of recorded ARM response from muscles for each side was as follows: (4.60 ± 0.7 on the non-operated side; median: 5) and (4.35 ± 1.9 on the operated side; median: 5). At least four ARM response of five muscles were recorded from 90% of the patients for both the non-operated and operated sides. The most recorded ARM response in a muscle was in TA (n = 38); the least recorded ARM response in a muscle was in BF-long head (n = 33). The numbers of the recorded ARM response from RF and VL and GC were 35, 36 and 36, respectively. The most common reasons of missing ARM response were unobtainable and excluded ARM response due to displacement of the needle during preoperative preparation and displacement of the needle during operation or unstable baseline, respectively.

Table 2 shows descriptive data for ARM response from muscles on both the non-operated and operated sides. Latency and amplitude values of ARM response from recorded muscles on the non-operated and operated sides were not statistically different.

The mean stimulus intensity for the non-operated and operated sides was as follows: 462.5 ± 112.8 (range 300–650 V; median: 475 V) and 520.0 ± 172.3 (range 300–1000 V; median 487.5 V) (p = 0.834). Only 30% of the patients were stimulated at more than 500 V on both the non-operated and operated sides. On patient 15, we did not obtain any ARM response from the muscles on the operated side, so we increased the stimulation intensity to 1000 V but without success. Patient 15 was excluded from the statistical analysis. Then we compared the stimulus intensity in all patients once more between the non-operated and operated sides, as follows: 486.2 ± 122.9 (range 300–750 V; median 475 V) and 501.3 ± 153.1 (range 300–850 V; median 475 V) (p = 0.838).

Table 3 demonstrates the mean latency and amplitude values of ARM response from the five muscles of interest, on both the non-operated and operated sides.

The age, weight, height and body mass index (BMI) of the patients showed no correlation with the number of recorded ARM response from the muscles or with the stimulus intensity on both the non-operated and operated sides (Table 4).

In all patients, the free-run recordings did not show any sustainable neurotonic discharges and there was no post-operative neurological deficit.

4 Discussion

IOM during hip surgeries to assess the functional integrity of the sciatic and femoral nerves of lumbar spinal roots has not been in common use. However, nerve injury

Table 1 Demographic features of the subjects, the number of recorded ARM responses from muscles and the mean stimulus intensity both for the non-operated and operated sides

Variables	Mean ± SD
Age	64.6 ± 13.9 (range 37–82)
Weight (kg)	75.4 ± 16.7 (range 52–105)
Height (cm)	166.9 ± 8.7 (range 150–186)
Body Mass Index (kg/m^2)	26.8 ± 4.9 (range 19–37)
Non-operated side	**Operated side**
Mean number of recorded ARM response from muscles ± SD (RF, VL, BF, TA, GC)	
4.6 ± 0.7 (range 3–5; median: 5)	4.35 ± 1.2 (range 0–5; median: 5)
Mean stimulus intensity ± SD	
462.5 ± 112.8 (range 300–650 V; median: 475 V)	520.0 ± 172.3 (range 300–1000 V; median: 487.5 V)

kg kilogram, *cm* centimeter, *m* meter, *SD* standard deviation, *ARM* anterior root muscle, *RF* rectus femoris, *VL* vastus lateralis, *BF* biceps femoris-long head, *TA* tibialis anterior, *GC* gastrocnemius, *V* volt

Table 2 The latency (ms) and the amplitude (µV) values of ARM responses from muscles on both the non-operated and operated sides

Non-operated side						Operated side						
Muscle	Variable	Min	Max	Mean (SD)	Median	Muscle	Variable	Min	Max	Mean (SD)	Median	P
RF N = 15	Latency (ms)	6.07	10.34	8.36 (1.1)	8.27	RF N = 20	Latency (ms)	6.93	13.48	9.20 (1.5)	9.10	0.06
	Amplitude (µV)	21.03	368.85	92.07 (81.7)	83.82		Amplitude (µV)	7.38	512.3	103.77 (131.4)	51.12	0.06
VL N = 18	Latency (ms)	7.86	19.60	9.90 (2.7)	9.21	VL N = 18	Latency (ms)	7.72	12.67	9.73 (1.5)	9.16	0.34
	Amplitude (µV)	14.25	508.20	129.1 (122.5)	101.49		Amplitude (µV)	1.60	500.00	109.02 (124.6)	77.25	0.33
BF N = 17	Latency (ms)	7.41	13.76	9.75 (1.4)	9.74	BF N = 16	Latency (ms)	6.34	12.17	9.28 (1.7)	9.21	0.44
	Amplitude (µV)	3.62	76.84	38.88 (21.9)	26.25		Amplitude (µV)	3.93	118.44	46.69 (36.6)	36.70	0.22
TA N = 19	Latency (ms)	12.01	18.89	15.19 (1.9)	15.50	TA N = 19	Latency (ms)	12.08	19.84	15.08 (1.9)	14.46	0.98
	Amplitude (µV)	2.34	530.00	117.47 (138.2)	56.75		Amplitude (µV)	9.11	562.62	171.79 (161.9)	103.27	0.42
GK N = 18	Latency (ms)	12.37	18.70	15.78 (1.8)	15.56	GK N = 18	Latency (ms)	11.80	23.20	15.49 (2.7)	15.33	0.40
	Amplitude (µV)	7.21	405.74	71.06 (89.7)	60.25		Amplitude (µV)	8.23	400.82	90.94 (103.4)	45.51	0.50

N number of subject, *SD* standard deviation, *RF* rectus femoris, *VL* vastus lateralis, *BF* biceps femoris-long head, *TA* tibialis anterior, *GK* gastrocnemius, *ms* millisecond, *µV* microvolt

$p < 0.05$

Table 3 Descriptive data for both the latency (ms) and the amplitude (µV) values of ARM responses of all muscles

Muscles	Median latency (ms)	Mean latency (SD) (ms)	Median amplitude (µV)	Mean amplitude (SD) (µV)
RF (n = 35)	8.84	**8.8 (1.4)**	66.10	**98.8 (114.5)**
VL (n = 36)	9.16	**9.8 (2.1)**	99.96	**119.1 (122.23)**
BF (n = 33)	9.54	**9.5 (1.6)**	34.56	**39.6 (30.3)**
TA (n = 38)	14.76	**15.1 (1.9)**	89.99	**144.6 (150.9)**
GK (n = 36)	15.4	**15.6 (2.4)**	55.71	**81.0 (99.9)**

Bold indicates the mean latency and amplitude values of ARM responses of all muscles

N number of subject, *SD* standard deviation, *RF* rectus femoris, *VL* vastus lateralis, *BF* biceps femoris-long head, *TA* tibialis anterior, *GK* gastrocnemius, *ms* millisecond, *µV* microvolt

Table 4 Correlation between demographic features, stimulus intensities and the number of recorded ARM responses

Variables	Age	Weight	Height	BMI
The stimulus intensity on the operated side				
Rho	0.136	−0.245	−0.244	−0.035
p	0.567	0.298	0.300	0.885
The stimulus intensity on the non-operated side				
Rho	0.365	−0.011	−0.272	0.202
p	0.114	0.962	0.247	0.394
The number of recorded ARM responses on the operated side				
Rho	−0.036	0.327	0.333	0.135
p	0.880	0.160	0.151	0.570
The number of recorded ARM responses on the non-operated side				
Rho	−0.430	0.141	0.324	−0.090
p	0.058	0.552	0.164	0.706

SI stimulus intensity, *BMI* Body Mass Index, *ARM* anterior root muscle, *rho* Spearman rho correlation

$p < 0.05$

is a rare but unpleasant complication of hip surgery and is more frequently seen in patients who need acetabular reconstruction for dysplasia and those undergoing revision arthroplasty. Number of complex hip surgeries is expected to be significantly increased in elderly patients due to longer life expectancy. Neurological deficits have to be avoided under all circumstances since recovery in the case of postoperative neurological deficit is difficult for elderly patients. TcMEP is the gold standard for intraoperative monitoring of motor function in order to avoid neurological damage, but it can only be done reasonably under general anesthesia. However, many of the elderly patients cannot be operated on under general anesthesia due to the risk of increased morbidity and mortality associated with general anesthesia and that´s why an alternative for TcMEP is needed for those patients. Spinal anesthesia is a widely used anesthetic technique for hip surgery in the elderly patients because of its efficacy, rapidity, minimal effect on mental status, reduction of blood loss, and protection against thrombo-embolic complications. Our study showed that the ARM response could easily be obtained during hip surgery under spinal anesthesia. In addition, the technique we used is non-invasive and safe. The ARM response might make it possible to assess the functional condition of the roots and the nerves intraoperatively. Monitoring ARM response during hip surgery under spinal anesthesia may be considered to be an alternative to TcMEPs in elderly patients.

The previous literature has shown that the peroneal division of the sciatic nerve is the most likely to be injured in THA [20–22]. In our study, TA was the most ARM response-recordable muscle. Thirty-eight ARM response recordings of the 40 were successfully obtained from TA. The second most recordable muscle showing the ARM response was the VL (n = 36), which could well be used for monitoring the femoral nerve. The least recorded muscle showing the ARM response was the BF-long head (n = 33). We managed to obtain at least 4 ARM response recordings both from the non-operated side (n = 18, 90% of the patients) and the operated side (n = 18, 90% of the patients). In only one of the 20 patients (5%) was it found impossible to record any ARM response from the muscles on the operated side. We did not get any ARM response from the operated side on Patient 15 even if we increased to stimulus intensity to 1000 V. One possible explanation for this is stronger stimulation intensity is not the sole determining factor of the action potential for generating lumbosacral roots under spinal anesthesia during hip surgery. The variability between individuals for the uptake and elimination of local anesthetic and the anatomical localization of stimulated roots could probably be related the unobtainable ARM response of patient 15. The uptake and elimination of local anesthetics in spinal anesthesia are influenced by the concentration of local anesthetic, surface area of the neuronal tissue exposed, lipid content of the neuronal tissue and blood flow to the tissue. The purpose of this study was to evaluate the ability to monitor ARM response during hip surgery under spinal anesthesia. To investigate the variability of stimulus threshold and the existence of ARM response fluctuations during the course of surgery were out of the scope of this study. Future research needs to be done to answer further questions.

The latency and amplitude values of the ARM response from muscles were not statistically different on either side. The mean stimulus intensity for the non-operated and operated sides did not show any difference even when we included the 1000 V stimulus intensity used with Patient 15 on the operated side or when it was excluded from the statistical analysis. Moreover, the age, height, weight and BMI of the patients were found not to be correlated with the stimulus intensity on either the non-operated or operated sides or the number of recorded ARM response from muscles. In 70% of the patients, our stimulation intensities were 500 V or less. However, one potential weakness of our method is that higher stimulation intensity is needed to get ARM response. It is possible to say that this high-voltage, transabdominal stimulation might stimulate distal of the surgical lesion. This issue needs to be searched in a systematic way in future research.

As descripted in Sect. 2, a paired stimulus of identical parameters was used with an ISI of 50 ms and duration of 0.5-1 ms for stimulating the lumbosacral roots and the nerves. In our recordings, we elicited two ARM responses. The first ARM response appeared after a first stimulation and the second ARM response which was obtained after 50 ms was almost the same configuration (amplitude and shape) as the first one. Considering needed higher stimulation intensity of this method and morphological similarity of two ARM responses, this second response was thought to be the activation of a direct efferent motor root rather than like the activation of the posterior roots. Indeed, our findings suggest that twin-stimulation might not be necessary to elicit ARM response unlike PRM reflex. Future research is warranted to compare these two stimulation methods.

In our study, descriptive values of the ARM response during hip surgery are defined for the first time. The mean latencies of ARM response from the muscles were respectively 8.8 ± 1.4 ms for RF; 9.8 ± 2.1 ms for VL; 9.5 ± 1.6 ms for BF-long head: 15.1 ± 1.9 ms for TA; 15.6 ± 2.4 ms for GC. One of main disadvantage of the ARM response was the unreliability of the amplitude values. So, a major limitation of this method is that the normative amplitude data indicate high inter-subject variability. As a consequence, normal lower boundaries of the ARM response amplitude cannot be defined because the mean − 2.5 SD is always < 0. Second, the onset of the ARM response was not accurate in some recordings because of an unstable baseline. For this reason, intraoperative alarm criteria under spinal anesthesia may be the persistent unilateral or bilateral loss of total ARM response and simultaneous neurotonic activity of the related muscle or muscles.

In fact, monitoring TcMEPs is the gold standard method of evaluating the corticospinal tract under total intravenous anesthesia and is important for voluntary movement [23]. In this study, we were unable to monitor the TcMEPs because spinal anesthesia during hip surgery was preferred by the surgeons in our hospital. Indeed, our findings show that it is possible to elicit the ARM response from sciatic and femoral nerves innervated muscles in patients who have undergone THA under spinal anesthesia. Finally, our study suggests that it is conceivable to use this high-voltage approach especially when tcMEP is not possible because of spinal anesthesia. It may also be appropriate to use this novel method combined with free-run EMG.

In conclusion, there is an unmet need to evaluation of sciatic and femoral nerves' functional integrity during complex hip surgery. This non-invasive technique may have a potential in patients who need acetabular reconstruction for dysplasia and those undergoing revision arthroplasty under spinal anesthesia, to detect early neurological deficit and to prevent irreversible neurological damage. More research is needed to evaluate advantages and outcomes of the ARM response during hip surgery.

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Compliance with ethical standards

Conflict of interest None of the authors has any conflicts of interest to disclose.

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