applied sciences

MDPI

Article

Clinical Neurophysiological Methods Verify Improvement in the Motor Neural Transmission in Patients with Surgically Treated Idiopathic Scoliosis in Long-Term Follow-Up

Przemysław Daroszewski [1], Juliusz Huber [2,*], Katarzyna Kaczmarek [2], Piotr Janusz [3], Paweł Główka [3], Marek Tomaszewski [3], Łukasz Kubaszewski [4], Mikołaj Dąbrowski [4] and Tomasz Kotwicki [3]

[1] Department of Organization and Management in Health Care, Poznań University of Medical Sciences, 28 Czerwca 1956 r. Street, no. 135/147, 61-545 Poznań, Poland; dyrektor@orsk.ump.edu.pl
[2] Department Pathophysiology of Locomotor Organs, Poznań University of Medical Sciences, 28 Czerwca 1956 r. Street, no. 135/147, 61-545 Poznań, Poland; katarzynakaczmarek@ump.edu.pl
[3] Department of Spine Disorders and Pediatric Orthopaedics, Poznań University of Medical Sciences, 28 Czerwca 1956 r. Street, no. 135/147, 61-545 Poznań, Poland; pjanusz@ump.edu.pl (P.J.); pawel.glowka@ump.edu.pl (P.G.); mtooma@wp.pl (M.T.); kotwicki@ump.edu.pl (T.K.)
[4] Adult Spine Orthopaedics Department, Poznan University of Medical Sciences, 28 Czerwca 1956 r. Street, no. 135/147, 61-545 Poznań, Poland; lkubaszewski@orsk.pl (Ł.K.); mdabrowski@ump.edu.pl (M.D.)
* Correspondence: juliusz.huber@ump.edu.pl; Tel.: +48-504-041-843

Abstract: The evaluation of patients after the surgical correction of idiopathic scoliosis in a long-term follow-up with clinical neurophysiological methods has not been presented in detail. This study aimed to compare the results of neurophysiological studies in 45 girls with scoliosis of Lenke types 1–3 performed pre- (T0) and postoperatively, 1 week after surgery (T1) and 6 months after surgery (T2). The parameter values of the surface electromyography while attempting maximal contraction (mcsEMG) and the transcranial motor-evoked potentials (MEPs) recorded in the anterior tibial muscles, as well as the electroneurography (ENG) of the peripheral transmission in the peroneal nerve motor fibers, were compared. The results indicate that efferent neural conduction function both centrally and peripherally, and TA muscle function slightly improved immediately after the surgical correction of scoliosis, and further normalization appeared after six months in the long-term follow-up (at $p = 0.03$). The sEMG recordings indicate that half a year after surgical treatment in IS patients, the TA muscle motor unit recruitment function, as well as the muscle strength evaluated with Lovett's scale, was comparable to the normal condition. The ENG recording results indicated a gradual reduction in the motor fiber injury symptoms, mainly of the axonal type, in the peroneal nerves. The surgeries also improved the lumbar ventral roots' neural transmission to a normal functional status. The MEP amplitude parameter values recorded after the surgical scoliosis corrections in T1 indicated a slight improvement in the efferent transmission of neural impulses within the fibers of the spinal tracts; in the long-term T2 observation period, they reached values comparable to those recorded in healthy volunteers, bilaterally. Preoperatively (T0), the results of all the neurophysiological study parameters in the IS patients were asymmetrical at $p = 0.036$–0.05 and recorded as worse on the concave side, suggesting the lateralization of neurological motor deficits. One week postoperatively (T1), this asymmetry was recorded as gradually reduced, showing almost no difference between the right and left sides six months later (T2). The presented algorithm for the neurophysiological assessments performed in the pre-, intra-, and long-term postoperative periods using the mcsEMG, MEP, and ENG neurophysiological examinations, together with the clinical studies, may help in the comprehensive functional evaluation of the spinal cord tracts and ventral root neural conduction, which allows the detection of the subclinical neurological changes related to scoliosis itself and the consequences of the corrective surgery. Such an evaluation can also be significant in making final decisions regarding IS surgeries and their personalization after attempting conservative treatments with bracing and kinesiotherapy. Neurophysiological studies, as a sensitive biomarker, allowed us to predict and ascertain the final result of IS treatment in the long-term follow-up, which showed the health status of patients as being comparable to that of healthy volunteers.

check for updates

Citation: Daroszewski, P.; Huber, J.; Kaczmarek, K.; Janusz, P.; Główka, P.; Tomaszewski, M.; Kubaszewski, Ł.; Dąbrowski, M.; Kotwicki, T. Clinical Neurophysiological Methods Verify Improvement in the Motor Neural Transmission in Patients with Surgically Treated Idiopathic Scoliosis in Long-Term Follow-Up. *Appl. Sci.* **2024**, *14*, 4105. https://doi.org/10.3390/app14104105

Academic Editor: Alexandros A. Lavdas

Received: 1 March 2024
Revised: 8 May 2024
Accepted: 11 May 2024
Published: 12 May 2024

Keywords: idiopathic scoliosis surgery; pre-, postoperative, and long-term neurophysiological recordings; electromyography; electroneurography; motor-evoked potentials

1. Introduction

Although the etiology of idiopathic scoliosis (IS) is considered to be multifactorial, involving the influences of pathologies related to the musculoskeletal system, developmental and genetic factors, nutritional deficiencies, early exposure to toxins, and hormonal dysregulation [1], neuropathological mechanisms occurring at the level of the brain and spinal cord may trigger or enhance the spine curvature progression and related neurological deficits [2]. The development of pathological lateral curvature and axial rotation of the spine during ontogenesis in patients with IS affects the anatomical relationships of the spinal cord in the vertebral canal, primarily leading to abnormalities in the activity of gray matter nerve centers and the transmission of afferent and efferent impulses in the axons of white matter funiculi [3,4]. The incidence of spinal cord pathology in pediatric patients with scoliosis has been reported to be frequently detected, even reaching 20%, with preoperative magnetic resonance imaging (MRI) demonstrating various intraspinal abnormalities [5,6]. Disorders in the conduction of neural impulses within the spinal ventral roots may lead to the development of neuropathy in the peripheral nervous system and, finally, to neurogenic changes in the muscular system as symptoms of secondary changes originating from IS [4]. Clinical neurophysiology diagnostics have proven the high incidence of the mentioned abnormalities before treatment and the axonal-type injury symptoms in peroneal motor fibers, which postoperatively improved on the concave side of IS in parallel with the lumbar ventral root neural motor conduction [7]. Although these pathologies can be considered subclinical, surgical intervention restores the proper relations between the lumbar ventral roots in the central spinal canal and symptoms resembling their decompression.

In the majority of IS patients, kinesiotherapeutic treatment [8,9] and bracing [10–13] for improving their body posture provide only partial benefits for slowing down the progression of the pathological curvature. Negrini et al. [14,15] concluded the necessity for surgical intervention in IS patients with a primary Cobb angle of 40–45 degrees, where a fast worsening of the pathology is expected. This supports the data from the studies by Diebo et al. [16] and Addai et al. [9], which indicated that 47% of patients were brace-eligible when the primary IS curvature ranged within 20–45 degrees, and 21% were candidates for surgical correction with Cobb angles of more than 45 degrees. The surgical posterior and anterior approaches for IS curvature correction, aiming at selective thoracolumbar fusions, are successfully realized. A three-dimensional symmetry of the affected spine while minimizing the number of fused levels is the purpose of surgical treatment [17]. Another fundamental aspect of surgical IS treatment is the restoration of sagittal balance. Back pain, disc–root conflicts, and progressive degenerative disk disorder may be the consequences of the non-treated disease [18]. The surgical correction of IS includes many procedures, during which the spinal cord, nerve roots, and key blood vessels are exposed to a risk of compromise or injury. The current data indicate that in 6.3% of patients, neurologic complications may appear due to various mechanisms, including indirect or direct trauma to the spinal cord, ischemia, or stretching during IS deformity correction [19]. Intraoperative neuromonitoring (IONM) provides a safe and useful warning to minimize the neurological risks in pediatric surgeries [20].

In patients with scoliosis, clinical assessment, including classical X-ray and neuroimaging, is a routine examination performed pre- and postoperatively [21,22], rarely in a long-term follow-up [23,24], aimed at indicating the validity of the surgical procedure and observing its effects in relation to the biomechanical and aesthetic features of the spine. In some cases, it influences the decision to perform a reoperation. In a review of the literature on this topic, it was found that if long-term clinical evaluations of patients with IS were performed, they usually involved the evaluation of radiographs. The results of available clinical tests assessing the function of the muscular and nervous systems were not reported. It seems that subclinical neurological deficits in IS patients that can be assessed with the available methods of evaluation are poorly detectable.

Neurophysiological assessment has the most important intraoperative significance when neuromonitoring the conduction of neural impulses within the spinal cord pathways [25]; however, preoperatively, in patients with IS, it supports the clinical assessments when making decisions about surgical treatment [26]. Few studies in the field of clinical neurophysiology presenting postoperative recordings, especially of motor-evoked potentials, proved an immediate functional improvement in the efferent conduction of spinal pathways in IS patients [7]. This does not imply that preoperative monitoring techniques are inherently more sensitive than intraoperative ones; different assessments, both pre- and intraoperative ones, serve different purposes and may provide complementary insights into the neurological aspects of idiopathic scoliosis.

The neurophysiological evaluation of patients after the surgical correction of idiopathic scoliosis in a long-term follow-up has not been presented in detail. Therefore, this paper aims to present the comparative bilateral results of surface-recorded electromyography (EMG) and motor-evoked potentials (MEP) recorded in the tibialis anterior muscle, as well as the results of peroneal nerve electroneurography (ENG), not only before and after the scoliosis corrections but also six months postoperatively. We intended to verify the main hypothesis concerning whether the effect of the direct improvement of the efferent conduction of neural impulses in the spinal cord pathways following curvature correction in IS patients remained unchanged or continued to progress in the long-term follow-up. The null hypothesis in this study was that there were no differences in the electromyographic, electroneurographic, and transcranial motor-evoked potential parameter values recorded bilaterally in muscles of the lower extremities in IS patients pre- and postoperatively in the long-term observation period.

2. Materials and Methods

2.1. Participants and Study Protocol

The data of 45 girls with IS treatment between 2019 and 2023 at the Wiktor Dega Orthopedic and Rehabilitation Hospital in Poznań, Poland, were selected for this study from the cohort of 372 patients. The principles of this selection are presented in Figure 1.

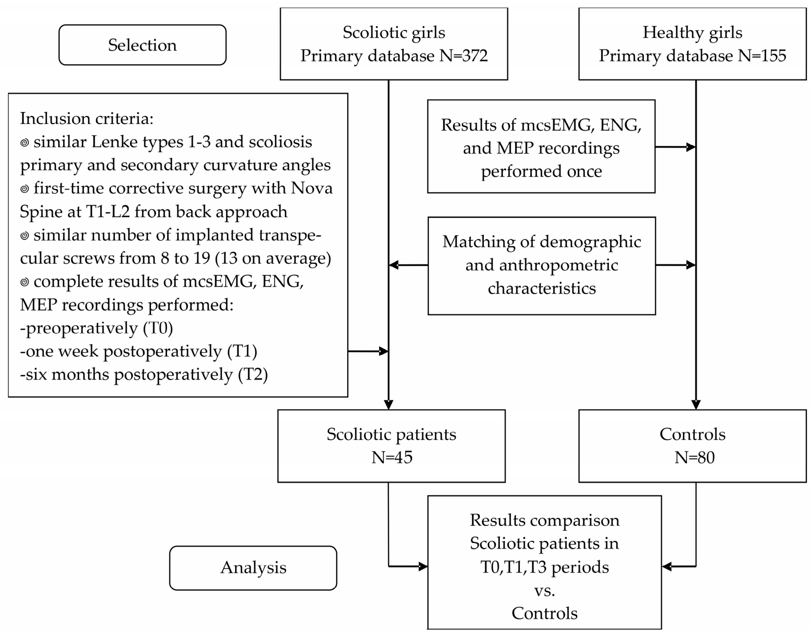

Figure 1. Flow chart of this study with the selection criteria for scoliotic subjects and healthy controls. Abbreviations: mcsEMG—tibialis anterior muscle maximal contraction surface electromyography

recording, ENG—peroneal nerve electroneurography recording, and MEP—tibialis anterior muscle motor evoked potential recording.

The inclusion criteria were as follows: primary right thoracic and secondary left lumbar IS with Cobb angles in similar ranges based on the measurements from anterior–posterior and lateral X-rays, Lenke types 1–3 (mainly 2) of IS [27], the employment of the same technique for the patients' surgeries using the Nova Spine corrective instrumentation with a similar number of implanted transpedicular screws between 8 and 19 (13 on average), data acquisition from the same set of three diagnostic clinical neurophysiology tests performed preoperatively (T0), one week postoperatively (T1), and six months after surgery (T2) (Table 1).

Table 1. Data on demographics, anthropometric measurements, and IS characteristics of the patients and healthy volunteers from the control group. Minimum, maximum, and mean values and standard deviations are presented, respectively.

Variable Group of Subjects	Age (years)	Height (cm)	Weight (kg)	BMI	Scoliosis Type	Cobb's Angle
Patients N = 45 ♀	9–17 14.8 ± 1.7	135–180 164.1 ± 2.5	28–82 52.7 ± 3.7	17.1–30.2 22.8 ± 4.3	Lenke 1 = 12 Lenke 2 = 26 Lenke 3 = 7	Primary 42–89 58.4 ± 5.8 Secondary 29–48 35.2 ± 3.8
Healthy volunteers Controls N = 80 ♀	8–17 13.9 ± 1.9	133–182 166.9 ± 2.3	28–85 53.1 ± 6.0	17.5–29.5 22.4 ± 3.5	NA	NA
p-value	0.228 NS	0.293 NS	0.232 NS	0.271 NS		

Abbreviations: IS—idiopathic scoliosis; ♀—female; NS—non-significant; NA—non-applicable. $p \leq 0.05$ determines statistically significant differences; p adjusted with Bonferroni correction ≤ 0.00512.

The IS patients were assessed with neurophysiological recordings three times. The tests included bilateral tibialis anterior (TA) muscle electromyography recordings during maximal contraction with surface electrodes (mcsEMG); peroneal nerve electroneurography (ENG) recorded in the extensor digitorum brevis (EXT) muscle following the electrical stimulation of motor fibers in the ankle; and motor-evoked potential (MEP) recordings in the tibialis anterior muscles following transcranial magnetic stimulation (TMS). The exclusion criteria were similar to the contraindications for diagnostic TMS and transcranial electrical stimulation utilized during the neuromonitoring procedures. They comprised having head trauma, epilepsy, or cardiac disease; using pacemakers or other implanted biomedical devices; and pregnancy [28]. There was no need to apply anesthetics, neither in the pre- nor postoperative observations. The patients were fully aware and cooperative.

The reference values for the parameters of mcsEMG, ENG, and MEP neurophysiological recordings were obtained from a control group of 80 healthy volunteers. To ensure the data comparability between patients and controls, the demographics (gender, age, height, and weight) were preliminarily matched during the data mining. Significant differences in age, height, and weight between the patients and healthy volunteers in the control group were not observed (Table 1).

The patients were surgically treated and clinically evaluated three times in the T0–T2 periods of observation by the same team of four experienced spine surgeons. Neurophysiological studies were performed by the same two neurophysiologists. The surgeons independently evaluated the anterior–posterior and lateral spinal X-rays and MRI, and the final results were arbitrarily determined in the final analysis. The manual muscle strength testing of the TA was performed using Lovett's scale (0–5), which consists of six grades that assess the different levels of muscle strength (from 0—no visible voluntary contraction of the muscle to 5—normal, maximal muscle strength). The neurophysiologists proceeded similarly after three stages of observation.

The ethical considerations were in agreement with the Helsinki Declaration. Approval was received from the Bioethical Committee of the University of Medical Sciences in Poznań, Poland (including the studies on healthy people) (decision no. 942/21). Each subject (and her parent/legal guardian) was informed about the aim of this study and gave their written consent to the examinations and data publication.

2.2. Treatment

Before the surgical treatment, 25 out of the 45 patients were treated with a Chêneau brace, and all of them had applied the physiotherapeutic exercises aimed at correcting body posture. During the scoliotic spinal surgery, the implantation of a Nova Spine corrective instrumentation system (Amiens, France) was carried out by a posterior approach in a prone position (Figure 2(Db)). The deformity was corrected following the pedicle polyaxial and monoaxial screw implantation and implementation of two corrective rods (5.5 mm in diameter) made of a titanium alloy (Figure 2(Dc)). The maneuvers of convex rod rotation, apical translation, segmental de-rotation, distraction on the concave side, and compression on the convex side were performed to obtain spinal fusion. All surgical procedures were applied under the control of X-ray C-arm and neuromonitoring navigations (Figure 2(Da,Dc)). Further details regarding the surgical procedures and intraoperative neurophysiological recordings are described elsewhere [7].

2.3. Neurophysiological Recordings

The principles of the neurophysiological studies' methodology performed in the three periods of observation (preoperatively—T0; postoperatively, 1 week after surgery—T1; and 6 months after surgery—T2) are presented in Figure 2. All patients were examined in a supine position. The tests were performed in the same diagnostic room with a controlled temperature of 22 °C. The KeyPoint Diagnostic System (Medtronic A/S, Skøvlunde, Denmark) was used to record all neurophysiological tests. During the T0–T2 periods of observation, the same neurophysiological tests were performed with the same conditions of stimulation and recording, with the same types of surface electrodes, in the same laboratory, with patients in the same position.

The surface electrodes were used for non-invasive recordings in the electromyographical studies (mcsEMG). They were bilaterally recorded in the tibialis anterior muscle (TA) (Figure 2(Aa)) to assess the motor unit recruitment while the patients attempted maximal muscle contraction for 5 s (Figure 2(Ab)). The electroconductive gel decreased the resistance between the electrode surface and the skin. Disposable Ag/AgCl surface-recording electrodes were applied (with an active surface of 5 mm^2). An active electrode was placed on the belly muscle, a reference electrode was placed on the distal tendon of the same muscle, and a ground electrode was mounted on the distal part of the lower extremity. The electrodes were consistently placed at the same distances in the T0–T2 periods of observation.

The Guidelines of the International Federation of Clinical Neurophysiology—The European Chapter [29–31] were followed during the mcsEMG recordings' acquisition and interpretation. The patients attempted three maximal muscle contractions for 5 s. The neurophysiologist selected the best recording with the highest mean amplitude measured peak to peak concerning the isoelectric line for analysis. The output measures from the mcsEMG recordings were the amplitude measured in µV and the frequency of muscle motor unit action potential recruitment measured in Hz. The frequency indices (FI; 3–0) based on the calculations of the motor units' action potential recruitment during maximal contraction were determined in the mcsEMG recordings, as well, where 3 = 95–70 Hz—normal, 2 = 65–40 Hz—moderate abnormality, 1 = 35–10 Hz—severe abnormality, and 0 = no contraction. All mcsEMG recordings in all subjects were performed at a base time of 80 ms/D and an amplification of 20–1000 µV/D. The upper 10 kHz and lower 20 Hz filters were adjusted in the recorder settings.

Figure 2. Photographs illustrating methodological principles of the neurophysiological studies repeated in T0–T2 periods of observation and treatment. (**A**)—Bilateral electromyography recordings with a pair of surface electrodes in the tibialis anterior muscle (r) were performed at rest (**a**) and while attempting maximal contraction (**b**). (**B**)—Bilateral electroneurography recordings in the extensor digitorum brevis muscle (r) were performed following the electrical stimulation of the motor fibers in the peroneal nerve in the ankle (s). (**C**)—Bilateral motor-evoked potential recordings were performed in the tibialis anterior muscle (r) following transcranial magnetic stimulation (TMS) (**a**). Preoperatively, this study also aimed to find the best "hot spot" place for transcranial magnetic stimulation (**b**) marked on the skull (**c**), which was used for the intraoperative neuromonitoring procedures. (**D**)—Bilateral recordings of the motor-evoked potential were also performed intraoperatively in the upper and lower extremity muscles including the anterior tibial muscle during the scoliosis corrective surgeries (**b**). The "hot spots" ascertained preoperatively were used for the transcranial motor cortex centers' excitation with the electrical stimuli delivered via subcutaneous electrodes (**a**). This study verified the correct conduction of the motor pathways of the spinal cord during bilateral procedures of corrective instrumentation implantation (**c**).

In each subject, bilateral electroneurography (ENG) recordings were performed (Figure 2B) to assess the peripheral conductivity of neural impulses in the motor fibers of the peroneal nerves. The test aimed to assess if the abnormal muscle function or the efferent transmission was caused by pathologies in the L5 ventral root fibers' neural conduction and/or the consequence of peripheral neuropathies. Applying the electrical stimulation with rectangular pulses of a 0.2 ms duration at a frequency of 1 Hz and an intensity ranging from 0 to 80 mA using bipolar stimulating electrodes placed over the skin along the anatomical passages of the nerve in the ankle evoked the compound muscle action potentials (M-wave CMAPs). The simultaneously recorded F-waves evoked potentials in the extensor digitorum brevis muscle (EXT) were assumed to verify the transmission of neuronal impulses in the motor fibers, peripherally and within the L5 ventral spinal roots, respectively. The ENG recordings were acquired with an amplification of 100–5000 µV/D and a 2–10 ms/D time base adjusted in the recorder settings. The outcome measures of the ENG were the amplitude (in µV) and latency (in ms) parameters of the M-waves, the inter-latencies of the recorded M–F waves (in ms), and the frequencies of the F-waves (usually not less than 14 while evoking 20 positive, successive recordings of M-waves). The test results obtained in patients were compared with the normative values recorded in healthy volunteer subjects. Other papers present further details regarding the methodology of the acquisition and interpretation of the ENG studies [32,33].

The motor-evoked potentials (MEPs) were induced with a magnetic circular coil (C-100; 12 cm in diameter) placed over the scalp in the area of the M1 motor cortex. The coil released a single, biphasic, 5 ms lasting magnetic stimulus (TMS; Figure 2(Ca)). A MagPro X100 magnetic stimulator (Medtronic A/S, Skøvlunde, Denmark) was used for the stimulus generation. The excitation was targeted mainly toward the cells of origin of the fibers of the corticospinal tract for the innervation of the lower extremity muscles and the whole corona radiata's excitation. All neural structures up to 3–5 cm deep were excited via the magnetic field stream delivered at a strength of 70–80% of the resting motor threshold (RMT; 0.84–0.96 T). Under such conditions, the cells of origin of the rubrospinal tract in the midbrain were probably excited. The MEPs were bilaterally recorded with surface electrodes on the TA muscles. The latency and amplitude parameters were the outcome measures to assess the primary motor cortex output and evaluate the global efferent transmission of neural impulses to effectors via the spinal cord descending tracts. The location of an optimal stimulation (a hot spot in the area where TMS elicited the largest recorded MEP amplitude; Figure 2(Cb,Cc)) was searched following the consecutive tracking distance of 5 mm from each other. The accurate photographic documentation of hot spots marked at similar locations of the transcranial stimulation aimed to ensure the reproducibility of the MEP recordings in T0–T2. The MEP amplitude was measured from peak to peak in the recording. The latency from the stimulus application marked by the artifact in the recording to the onset of the positive inflection of the potential was analyzed. Subjects did not report the stimulation as painful. During MEP acquisition, the low-pass filter of the recorder was set to 20 Hz, the high-pass filter to 10 kHz, the time base to 10 ms/D, and the amplification of signals to between 200 and 5000 µV. A bandwidth of 10 Hz to 1000 Hz, a digitalization rate of 2000 samples per second, and channels were used during the recordings. The methodology of the MEP recordings has been described in detail elsewhere [34,35].

To secure and increase the safety of IS surgical correction, neuromonitoring sessions were performed in the theatre using the ISIS recording system (Inomed Medizintechnik, Emmendinger, Germany) (Figure 2(Dc)). A motor-evoked potential was induced as a result of transcranial electrical stimulation (TES; Figure 2(Da)) in the areas of the cortical motor fields for the innervation of the thumb and selected muscles of the lower extremities. A sequence of four stimuli, with a single pulse with a 500 µs duration and an intensity of 105 mA on average, were applied via bipolar subcutaneous electrodes. According to the previous description, we used our experience with applying the surface electrodes for the MEP recordings of the TA and the muscles of other upper and lower extremities [7].

The choice, in this study, to present the results of the MEP and sEMG recordings for the tibialis anterior muscle as the key muscle was based on the comparisons of these recorded parameters being the most often presented in scientific reports by other authors related to the treatment of IS patients, wherein neurophysiological tests were utilized for their evaluation.

2.4. Statistical Analysis

Statistica, version 13.1 (StatSoft, Kraków, Poland), was used to analyze the data. The descriptive statistics were the minimal and maximal values (range) with the means and standard deviations (SDs). The median value was used only to express the results of the strength muscle manual testing of the tibialis anterior muscle on Lovett's scale (0–5) during patients' clinical evaluations. The normality distribution and homogeneity of variances were studied using the Shapiro–Wilk and Levene's tests. The frequency mcsEMG index and recorded F-wave frequencies were of the ordinal-scale type, while the amplitudes and latencies of the other analyzed neurophysiological tests were of the interval-scale type. None of the collected data represented a normal distribution or were of the ordinal-scale type. Wilcoxon's signed-rank test was used to compare the differences between results obtained before and after treatment and the results for the T0, T1, and T2 periods of observation. In the case of independent variables, the non-parametric Mann–Whitney test was used. Any p-values of <0.05 were considered statistically significant. We also compared the differences with those calculated using the Bonferroni correction at $p < 0.05$. The cumulative data from the mcsEMG, ENG, and MEP parameter recordings performed on both sides were used for comparisons between T0, T1, and T2. The results from all neurophysiological tests were also calculated for the group of healthy subjects to obtain the normative parameter values for comparisons between the health statuses of the patients and controls. Any significant differences in the values of the parameters recorded in the neurophysiological tests on the left and right sides in the controls vs. the IS patients were detected. Attention was paid to matching the demographic and anthropometric properties of the patients and healthy controls during the preliminary data mining. Statistical software (StatSoft, version 13.1, Kraków, Poland) was used to determine the required sample size using the primary outcome variables of the sEMG and MEP amplitudes recorded in the TA muscles before and after treatment with a power of 80% and a significance level of 0.05 (two-tailed). The mean and standard deviation (SD) were calculated using the data obtained from the first 20 patients, and the sample size determination software estimated that more than 40 patients were needed for this study. The same software estimated the number for the control group to be 40. Nevertheless, we doubled this population to provide the most reliable normative data for statistical analysis.

3. Results

In the vast majority of patients described in this paper, the Chêneau brace and physiotherapeutic exercises, if applied, were not effective forms of treatment for diminishing the progression of scoliosis. Various abnormalities in the spinal neuronal structures were found in the MRI evaluation in 35% of all studied IS patients. Detailed clinical neurological assessments using classical evaluation methods such as sensory perception, reflex testing, and manual muscle strength testing were not expected to be described in the current work. We focused on presenting the results of neurophysiological recordings in IS patients. Nevertheless, on a scale of 0–5, the manual muscle testing showed the strength of the TA muscles to have a median score of 3–4 in the T0 period of observation and 4–5 in T2 at $p = 0.046$, especially on the concave side of the scoliosis.

The mcsEMG amplitude, ENG, and MEP amplitude parameter values recorded in the observation period between T0 and T1 significantly differed at $p = 0.032$–0.049, showing a tendency for an increase in values (see Table 2, right side). This tendency gradually increased for all parameters recorded in all tests performed in the observation periods between T0 and T2, where the differences were ascertained at $p = 0.019$–0.045. This suggests that patients' efferent neural conduction function (both centrally and peripherally) as well as TA muscle function improved immediately after the surgical correction of scoliosis and further normalization appeared after six months in the long-term follow-up.

A comparison of more amplitudes than FI parameters in the mcsEMG recordings indicated that patients' TA muscle motor unit activity differed in T0 from the healthy controls at $p = 0.025$–0.037, but this difference became less significant in T1 at $p = 0.026$–0.042 and the least significant in T2 at $p = 0.043$–0.046 (Table 2, see also Figures 3(Aa–Ca) and 4A). It seems that the TA muscle motor unit recruitment function within 6 months from the surgical treatment in IS patients is comparable to the normal condition.

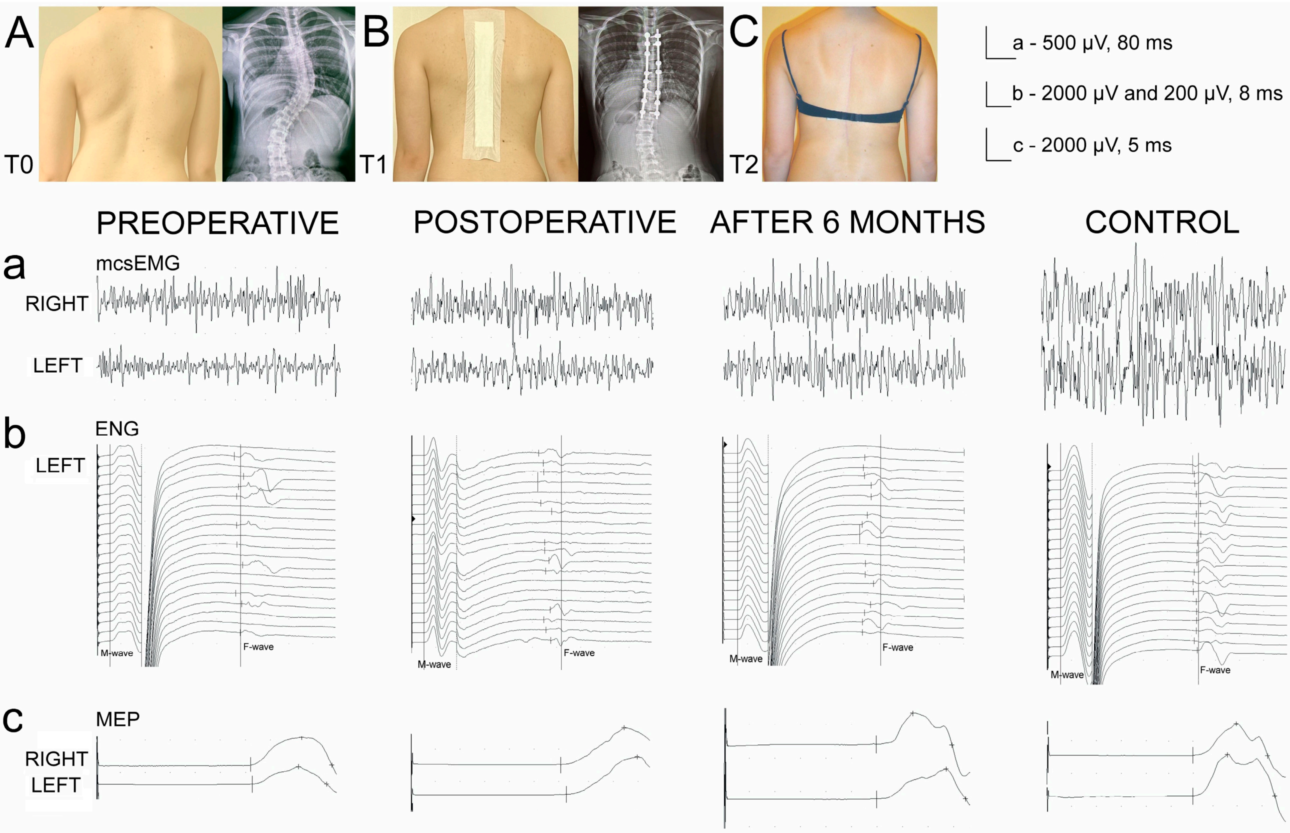

Figure 3. Examples of mcsEMG (**a**), ENG (**b**), and MEP (**c**) recordings performed on the right and left sides in three periods of observation ((**A**) T0—1 day before surgery; (**B**) T1—1 week after surgery; and (**C**) T2—6 months after surgery) in one of the IS patients. Control recordings from one of the healthy volunteers are shown in the right part of the figure for comparison. The rear view of the Lenke 1 IS patient's body silhouette and X-rays in A and B present the diminishing of the lateral spine curvature from 60- to 9-degree Cobb's angle, respectively. Calibration bars for amplification (vertical) and time base (horizontal) that were set during neurophysiological recordings are shown in the right-upper corner of the figure. Abbreviations: mcsEMG—tibialis anterior muscle maximal contraction surface electromyography recording, ENG—peroneal nerve electroneurography recording, and MEP—tibialis anterior muscle motor-evoked potential recording.

Table 2. Summary of comparison of the results from electromyographical, electroneurographical, and motor-evoked potential recordings performed in 45 patients pre- (T0) and postoperatively (T1—one week after surgery; T2—six months after surgery) and in 80 healthy volunteers (control).

Test Parameter	Side	Control	Scoliosis Side	Patients Preoperative T0 (1 Day before Surgery)	Control vs. Patients Preoperative T0	Patients Postoperative T1 (1 Week After Surgery)	Control vs. Patients Postoperative T1	Patients Postoperative T2 (6 Months After Surgery)	Control vs. Patients Postoperative T2	Patients Preoperative T0 vs. Postoperative T1	Patients Preoperative T0 vs. Postoperative T2
		Min.–Max. Mean ± SD		**Min.–Max. Mean ± SD**	***p*-Value**	**Min.–Max. Mean ± SD**	***p*-Value**	**Min.–Max. Mean ± SD**	***p*-Value**	***p*-Value**	***p*-Value**
Tibialis anterior muscle electromyography during maximal contraction (mcsEMG)											
Amplitude (µV)	R	600–2600 890.6 ± 104.2	Convex	300–2500 548.2 ± 95.4	**0.037**	300–2650 677.3 ± 94.8	**0.042**	400–2700 725.5 ± 93.3	**0.046**	**0.044**	**0.039**
	L	600–2550 887.8 ± 91.5	Concave	260–2500 453.1 ± 82.1	**0.031**	250–2550 572.1 ± 91.9	**0.041**	200–1950 663.1 ± 92.0	**0.043**	**0.046**	**0.040**
p-value	R vs. L	0.327	Convex vs. concave	**0.049**	NA	0.050	NA	0.051	NA	NA	NA
FI (3-0)	R	3.0–3.0 3.0	Convex	3.0–1.0 2.3 ± 0.4	**0.032**	3.0–1.0 2.4 ± 0.3	**0.031**	3.0–2.0 2.8 ± 0.4	**0.045**	0.054	**0.035**
	L	3.0–3.0 3.0	Concave	3.0–1.0 2.2 ± 0.5	**0.025**	3.0–1.0 2.3 ± 0.5	**0.026**	3.0–2.0 2.7 ± 0.4	**0.044**	0.061	**0.031**
p-value	R vs. L	NS	Convex vs. concave	**0.046**	NA	**0.045**	NA	**0.045**	NA	NA	NA
Peroneal nerve ENG recorded in the extensor digitorum brevis muscle after stimulation at the ankle											
M-wave Amplitude (µV)	R	3000–12,500 6760.1 ± 965.1	Convex	1500–9800 2702.1 ± 353.1	**0.007**	1400–10,500 2804.1 ± 362.7	**0.008**	1400–11,000 3011.3 ± 332.0	**0.009**	**0.041**	**0.036**
	L	3000–11,600 6558.4 ± 877.3	Concave	1400–9800 2525.3 ± 422.5	**0.008**	1500–10,000 3025.4 ± 421.9	**0.009**	1400–1050 3191.4 ± 406.7	**0.011**	**0.036**	**0.033**
p-value	R vs. L	0.228	Convex vs. concave	**0.050**	NA	**0.048**	NA	**0.049**	NA	NA	NA
M-wave Latency (ms)	R	3.2–5.4 4.5 ± 1.1	Convex	3.2–6.4 5.3 ± 1.4	**0.042**	3.5–6.6 5.3 ± 1.3	**0.041**	3.2–6.3 4.6 ± 1.3	0.068	0.167	**0.039**
	L	3.3–5.5 4.6 ± 1.1	Concave	3.5–6.5 5.5 ± 1.3	**0.034**	3.5–6.6 5.1 ± 1.4	**0.037**	3.3–6.2 4.7 ± 1.4	0.075	**0.049**	**0.042**
p-value	R vs. L	0.328	Convex vs. concave	**0.048**	NA	**0.046**	NA	0.061	NA	NA	NA

Table 2. *Cont.*

Test Parameter	Side	Control	Scoliosis Side	Patients Preoperative T0 (1 Day before Surgery)	Control vs. Patients Preoperative T0	Patients Postoperative T1 (1 Week After Surgery)	Control vs. Patients Postoperative T1	Patients Postoperative T2 (6 Months After Surgery)	Control vs. Patients Postoperative T2	Patients Preoperative T0 vs. Postoperative T1	Patients Preoperative T0 vs. Postoperative T2
		Min.–Max. Mean ± SD		**Min.–Max. Mean ± SD**	***p*-Value**	**Min.–Max. Mean ± SD**	***p*-Value**	**Min.–Max. Mean ± SD**	***p*-Value**	***p*-Value**	***p*-Value**
F-wave Frequency (x/20 M-waves)	R	14–20 17.5 ± 1.3	Convex	10–16 12.1 ± 1.5	**0.043**	11–19 14.0 ± 1.4	**0.048**	12–18 15.6 ± 1.3	0.055	**0.048**	**0.045**
	L	14–20 17.8 ± 1.4	Concave	8–15 11.1 ± 1.5	**0.042**	11–17 13.9 ± 1.3	**0.046**	12–17 14.8 ± 1.4	0.052	**0.048**	**0.045**
p-value	R vs. L	0.318	Convex vs. concave	**0.050**	NA	0.074	NA	0.061	NA	NA	NA
M–F waves Inter-latency (ms)	R	38.6–49.2 44.4 ± 2.2	Convex	39.1–57.3 50.4 ± 2.7	**0.045**	38.2–57.3 48.9 ± 2.4	**0.048**	38.5–49.0 45.1 ± 2.1	0.062	**0.049**	**0.038**
	L	38.0–49.4 44.7 ± 2.3	Concave	40.1–59.8 53.7 ± 2.2	**0.031**	38.1–56.9 48.4 ± 2.7	**0.047**	38.3–51.3 47.1 ± 2.8	**0.047**	**0.047**	**0.046**
p-value	R vs. L	0.481	Convex vs. concave	**0.046**	NA	0.138	NA	**0.045**	NA	NA	NA
TMS-induced MEPs recorded in tibialis anterior muscle											
Amplitude (µV)	R	1200–3550 1697.2 ± 96.6	Convex	300–1350 412.5 ± 92.1	**0.010**	600–2500 953.1 ± 95.2	**0.027**	950–2850 1488.3 ± 98.4	**0.046**	**0.034**	**0.018**
	L	1000–2950 1609.1 ± 78.6	Concave	250–1150 181.4 ± 66.1	**0.009**	400–1800 749.3 ± 88.2	**0.019**	800–2700 1312.7 ± 87.2	**0.041**	**0.032**	**0.019**
p-value	R vs. L	0.291	Convex vs. concave	**0.036**	NA	**0.043**	NA	**0.048**	NA	NA	NA
Latency (ms)	R	24.9–31.9 28.7 ± 1.3	Convex	27.6–36.1 32.1 ± 2.2	**0.036**	28.9–39.1 31.7 ± 2.8	**0.044**	25.7–34.2 29.3 ± 2.4	0.072	0.059	**0.045**
	L	25.3–32.3 29.1 ± 1.4	Concave	28.4–37.8 32.8 ± 2.4	**0.039**	30.5–41.0 33.6 ± 2.6	**0.037**	26.8–35.3 29.9 ± 2.3	0.064	0.056	**0.047**
p-value	R vs. L	0.271	Convex vs. concave	0.064	NA	**0.049**	NA	0.066	NA	NA	NA

Abbreviations: mcsEMG—muscle maximal contraction surface electromyography recordings; FI—frequency index (3-0) (frequency of motor unit action potential recruitment during maximal contraction: 3—95–70 Hz, normal; 2—65–40 Hz, moderate abnormality; 1—35–10 Hz, severe abnormality; and 0—no contraction); ENG—electroneurography recordings; TMS—transcranial magnetic stimulation; MEP—muscle motor evoked potential recording; NA—non-applicable; $p < 0.05$ determines statistically significant differences marked in bold.

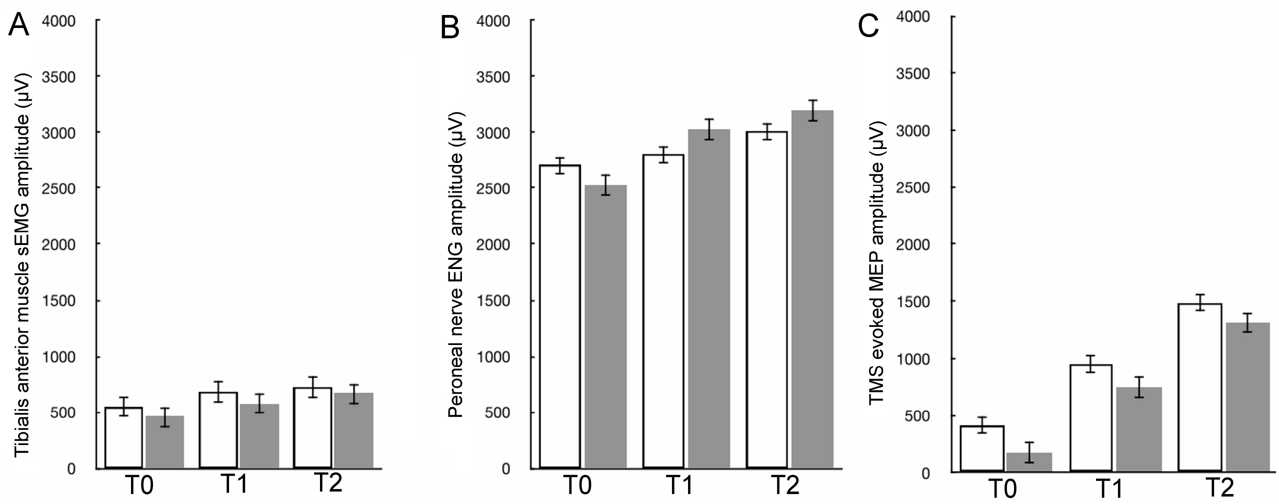

Figure 4. Comparison of the amplitude values from mcsEMG (**A**), ENG (**B**), and MEP (**C**) recordings performed on the convex (white bars) and concave (grey bars) sides of the secondary, lumbar curvature in three periods of observation (T0—1 day before surgery, T1—1 week after surgery, and T2—6 months after surgery) in IS patients.

In the ENG recordings performed preoperatively, early postoperatively, and after a long-term observation period, the tendency to observe increased values of M-wave amplitudes (at p = 0.007–0.011; see also Figure 4B) and decreased values of latencies (at p = 0.034–0.075; Table 2) indicated the gradual reduction in the symptoms of peroneal motor fiber injury of mainly the axonal type. The parallel change in the increase in the F-wave frequency parameter values in the ENG recordings following the application of twenty electrical stimuli (p = 0.042–0.05) provides evidence that the surgeries also improved the lumbar ventral roots' neural transmission (Figure 3(Ab–Cb)) to a functional status considered normal. The M–F wave inter-latency parameter analysis in T0–T2 revealed a similar improvement at p = 0.031–0.062. In healthy volunteers, the strength of the electrical current to evoke the maximal M-wave amplitudes in the ENG recordings ranged from 17 to 39 mA with a mean of 25.4 $\pm$ 2.1 mA, while in patients in the T2 period of observation, it ranged from 30 to 45 mA (with a mean of 27.1 $\pm$ 1.9 mA), suggesting a lower, more physiological threshold of excitation for the motor fibers of the peroneal nerves.

A difference between the parameter values of the MEP amplitudes in the recordings of healthy volunteers and patients before surgery was observed at p = 0.009–0.01 (Table 2, bottom; see also Figures 3(Ac) and 4C). After the surgical scoliosis correction in T1 (Figures 3(Bc) and 4C), this change was observed at p = 0.019–0.027, indicating a slight improvement in the efferent transmission of neural impulses within the fibers of the spinal tracts. In the long-term T2 observation period, this difference further diminished and the amplitudes differed only at p = 0.041–0.046, bilaterally (Figures 3(Cc) and 4C).

Preoperatively (T0), the results of all the neurophysiological study parameters in the IS patients were asymmetrical at p = 0.036–0.05 and recorded as worse on the concave side, suggesting the lateralization of neurological motor deficits (Table 2; Figure 3(Aa,Ac)). One week postoperatively (T1), this asymmetry was recorded as gradually reduced (Figure 3(Ba,Bc)), showing almost no difference between the right and left sides six months later (T2) (Figure 3(Ca,Cc)).

4. Discussion

The results of this study in patients surgically treated for idiopathic scoliosis confirmed the previous findings in [7], namely, that the transmission of efferent neural impulses in the spinal cord tracts and within the fibers of the peripheral nervous system slightly improves immediately after the surgical correction of scoliosis. Moreover, we ascertained the further normalization of the motor function together with the improvement of TA muscle motor unit recruitment half a year after the surgical treatment in IS patients, in which the mcsEMG parameter values are comparable to those of the normal condition.

Apart from revealing the improvements regarding biomechanical and aesthetic features of the spine following the applied surgeries for IS patients in clinical studies, the neurophysiological approach enables the investigation of the lateralization of the neurological motor deficits, which are gradually reduced postoperatively, showing almost no difference between the right and left sides during long-term observation. Although the test results referring to the efferent function evaluation presented in Table 2 are consistent and complementary, one can raise the objection that they were shown in patients with IS representing different types of scoliotic curvature according to the classification of Lenke et al. [27], which might be one of this study's limitations. The patients examined in this study mostly presented type 2 curvature, with the main right-sided curvature of the spine in the thoracic vertebrae and, to a lesser extent, the secondary one with an angle and opposite direction in the lumbar vertebrae, which is excessive in type 3 curvature. These cases are different from the type of scoliosis with an exclusively thoracic angle of curvature occurring in type 1. However, a greater decrease in the amplitude parameter and a slight increase in the latency parameter of MEPs recorded bilaterally in the TA muscle were similarly observed on the concave side of the scoliosis, along with changes in the conductivity of the roots of the lumbar neuromeres, with consequences on the symptoms of neuropathy within the lower limb nerves on the same side. Nevertheless, the possible variations in the pathology patterns that are reflected in the abnormalities found in the functional studies can only be explained by structural MRI studies.

The clinical evaluation of the IS patients in this study revealed the changes in the TA muscle strength from a median score of 3–4 in the T0 observation period to 4–5 in T2 at $p = 0.05$, especially on the concave side of the scoliosis. A possible explanation for these discrete differences in the motor performance improvement measured by the clinical method is its low resolution and resulting low precision [31]. However, it is still a widely used and recognized method in clinical practice. This study's neurophysiological methods for assessing motor function are scaled in microvolts and milliseconds. Hence, their results enable the detection of discrete differences in improvements in the neurological status of patients with musculoskeletal dysfunction of various etiologies, including patients with scoliosis.

A possible explanation for the immediate improvement of the overall efferent conduction shown in the results of the sEMG, ENG, and MEP studies after IS spinal surgery in the T1 observation period may be the restoration of normal anatomical and functional relationships between the neural structures in the vertebral canal of the deformed spine, mainly through surgical procedures with 3D curvature correction. This applies not only to axons in the lateral and ventral funiculi of the white matter but also to the spinal roots. This is clearly visible in the results of the ENG tests, showing symptoms of axonal damage in the motor fibers of the peroneal nerves (M-wave parameter abnormalities), recovering mainly on the concave side of the scoliosis, as well as in the tests of nerve impulse conduction in the ventral roots (showing a decreased frequency of the recorded F-wave), which suggests that de-rotation and distraction may result in the restoration of normal relationships between the lumbar ventral roots in the central spinal canal, resembling their decompression. It can be assumed that the significant improvement in the efferent conduction visible in the test results during the T2 observation period is the result of structural or more functional regeneration processes occurring in the spinal cord funiculi and/or the spinal ventral root structures.

The results of the presented study are unique, and it is difficult to compare them with the results of similar studies presented by other authors because they concern the functional assessment of patients after IS surgery in a long-term follow-up, and the results presented so far on this topic were postoperative X-ray evaluations. No evaluation using the clinical neurological methods on IS patients has been provided in previous studies, neither was this the aim of the present study. A comparison of the MEP parameter values in this study recorded in the TA muscle with the reports of other authors yields different data [36,37]. The only consistent comparison refers to the latency parameter value presented by Lo et al. [38] and earlier by Edmonds et al. [39], but the mean amplitude parameter value of about 500 μV is far beyond the one calculated in our MEP recordings. Moreover, the data cited above mainly come from intraoperative neuromonitoring observations accompanying scoliosis correction, rather than diagnostic data recorded postoperatively.

One might object to the use of the tibialis anterior muscle of the lower extremities for neurophysiological assessments instead of the paraspinal muscles, which meet the criteria for the functional assessment of motor function in patients with IS more effectively because preoperatively, these muscles show asymmetric activity in the motor units [4]. However, it should be remembered that these muscles are surgically incised and retracted in the midline to expose the surgical field during the curvature correction, and a comparison between their preoperative and postoperative function, especially in a short-term follow-up, would be fraught with inevitable iatrogenic structural damage. Hence, the MEP and sEMG recordings using the surface electrodes in the tibialis anterior muscle bilaterally are not only more widely used for pre- and postoperative diagnostic purposes but their activity has also been proven to be precise enough for intraoperative monitoring [40,41].

5. Conclusions

The presented algorithm for the neurophysiological assessments performed at the pre-, intra-, and long-term postoperative stages using mcsEMG, MEP, and ENG neurophysiological examinations represents an example of a comprehensive functional evaluation of the spinal cord's and ventral roots' neurological status. This allows for the detection of subclinical abnormalities in neural transmission related to scoliosis itself and the suggestion of procedures for surgical correction.

Although the aim of avoiding neurological complications during scoliosis surgery will always remain the principal task of intraoperative neuromonitoring, it seems worth demonstrating how the subtle abnormalities in the neurological status of IS patients can be improved with regular scoliosis surgical treatment. Future studies should concern the evaluation of IS patients' neurological status before and after surgery with the available clinical tools in the absence of descriptions of the cohort group. Neurophysiological studies, as a sensitive biomarker, allow for ascertaining the final result of IS treatment in a long-term follow-up, which shows the health status of patients compared with healthy volunteers.

Author Contributions: Conceptualization, P.D., J.H. and T.K.; methodology, P.D., J.H., K.K. and T.K.; software, J.H.; validation, P.D., J.H., K.K. and T.K.; formal analysis, P.D., J.H., K.K. and T.K.; investigation, P.D., J.H., K.K., P.J., P.G., M.T., Ł.K., M.D. and T.K.; resources, P.D. and J.H.; data curation, P.D., J.H., K.K. and T.K.; writing—original draft preparation, P.D. and J.H.; writing—review and editing, P.D., J.H., P.J., P.G., M.T., Ł.K., M.D. and T.K.; visualization, J.H.; supervision, P.D., J.H. and T.K.; project administration, P.D. and J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Bioethics Committee of Poznan University of Medical Science, (decision no 942/21, dated 13 January 2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: All the data generated and analyzed during this study are included in this published article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Burwell, R.G.; Dangerfield, P.H.; Lowe, T.G.; Margulies, J.Y. (Eds.) *Etiology of Adolescent Idiopathic Scoliosis: Current Trends and Relevance to New Treatment Approaches, State of the Art Reviews*; Hanley & Belfus, Incorporated: Philadelphia, PA, USA, 2000; ISBN 1560533331/9781560533337.
2. Lowe, T.G.; Edgar, M.; Margulies, J.Y.; Miller, N.H.; Raso, V.J.; Reinker, K.A.; Rivard, C.H. Etiology of idiopathic scoliosis: Current trends in research. *J. Bone Jt. Surg.* **2000**, *82*, 1157–1168. [CrossRef] [PubMed]
3. Hawes, M.C.; O'Brien, J.P. The transformation of spinal curvature into spinal deformity: Pathological processes and implications for treatment. *Scoliosis* **2000**, *1*, 3. [CrossRef] [PubMed]
4. Huber, J.; Rogala, P. Etiopathogenesis of the adolescent idiopathic scoliosis based on neuroimaging and neurophysiological examinations with the special emphasis on motor evoked potentials (MEP). *Stud. Health Technol. Inform.* **2012**, *176*, 446.
5. Gupta, P.; Lenke, L.G.; Bridwell, K.H. Incidence of neural axis abnormalities in infantile and juvenile patients with spinal deformity. Is a magnetic resonance image screening necessary? *Spine* **1998**, *23*, 206–210. [CrossRef] [PubMed]
6. Winter, R.B.; Lonstein, J.E.; Heithoff, K.B.; Kirkham, J.A. Magnetic resonance imaging evaluation of the adolescent patient with idiopathic scoliosis before spinal instrumentation and fusion. A prospective, double-blinded study of 140 patients. *Spine* **1997**, *22*, 855–858. [CrossRef] [PubMed]
7. Daroszewski, P.; Huber, J.; Kaczmarek, K.; Janusz, P.; Główka, P.; Tomaszewski, M.; Domagalska, M.; Kotwicki, T. Comparison of Motor Evoked Potentials Neuromonitoring Following Pre- and Postoperative Transcranial Magnetic Stimulation and Intraoperative Electrical Stimulation in Patients Undergoing Surgical Correction of Idiopathic Scoliosis. *J. Clin. Med.* **2023**, *12*, 6312. [CrossRef] [PubMed]
8. Negrini, S.; Antonini, G.; Carabalona, R.; Minozzi, S. Physical exercises as a treatment for adolescent idiopathic scoliosis. A systematic review. *Pediatr. Rehabil.* **2003**, *6*, 227–235. [CrossRef]
9. Addai, D.; Zarkos, J.; Bowey, A.J. Current concepts in the diagnosis and management of adolescent idiopathic scoliosis. *Child's Nerv. Syst.* **2020**, *36*, 1111–1119. [CrossRef]
10. Negrini, S.; Minozzi, S.; Bettany-Saltikov, J.; Zaina, F.; Chockalingam, N.; Grivas, T.B.; Kotwicki, T.; Maruyama, T.; Romano, M.; Vasiliadis, E.S. Braces for idiopathic scoliosis in adolescents. *Spine* **2010**, *35*, 1285–1293. [CrossRef]
11. Diebo, B.G.; Segreto, F.A.; Solow, M.; Messina, J.C.; Paltoo, K.; Burekhovich, S.A.; Bloom, L.R.; Cautela, F.S.; Shah, N.V. Adolescent idiopathic scoliosis care in an underserved inner-city population: Screening, bracing, and patient- and parent-reported outcomes. *Spine Deform.* **2019**, *17* (Suppl. S10), S213. [CrossRef]
12. Kelly, J.; Shah, N.; Freetly, T.; Dekis, J.; Hariri, O.; Walker, S.; Borrelli, J.; Post, N.H.; Diebo, B.G.; Urban, W.P.; et al. Treatment of adolescent idiopathic scoliosis and evaluation of the adolescent patient. *Curr. Orthop. Pract.* **2018**, *29*, 424–429. [CrossRef]
13. Pepke, W.; Morani, W.; Schiltenwolf, M.; Bruckner, T.; Renkawitz, T.; Hemmer, S.; Akbar, M. Outcome of Conservative Therapy of Adolescent Idiopathic Scoliosis (AIS) with Chêneau-Brace. *J. Clin. Med.* **2023**, *12*, 2507. [CrossRef] [PubMed]
14. Negrini, S.; Aulisa, L.; Ferraro, C.; Fraschini, P.; Masiero, S.; Simonazzi, P.; Tedeschi, C.; Venturin, A. Italian guidelines on rehabilitation treatment of adolescents with scoliosis or other spinal deformities. *Eur. Med.* **2005**, *41*, 183–201.
15. Negrini, S.; Donzelli, S.; Aulisa, A.G.; Czaprowski, D.; Schreiber, S.; de Mauroy, J.C.; Diers, H.; Grivas, T.B.; Knott, P.; Kotwicki, T.; et al. SOSORT guidelines: Orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth. *Scoliosis Spinal Disord.* **2018**, *13*, 3. [CrossRef] [PubMed]
16. Diebo, B.G.; Segreto, F.A.; Mixa, P.J.; Day, L.M.; Kaur, H.; Burekhovich, S.A.; Lavian, J.D.; Beyer, G.; Challier, V.; Naziri, Q.; et al. P84—Adolescent Idiopathic Scoliosis Care in an Underserved Inner-City Population: Screening, Bracing, Patients' and Parents' Reported Outcomes. *Spine J.* **2017**, *17*, S213. [CrossRef]
17. Patel, P.N.; Upasani, V.V.; Bastrom, T.P.; Marks, M.C.; Pawelek, J.B.; Betz, R.R.; Lenke, L.G.; Newton, P.O. Spontaneous lumbar curve correction in selective thoracic fusions of idiopathic scoliosis: A comparison of anterior and posterior approaches. *Spine* **2008**, *33*, 1068–1073. [CrossRef] [PubMed]
18. Luk, K.D.K.; Vidyadhara, S.; Lu, D.S.; Wong, Y.W.; Cheung, W.Y.; Cheung, K.M.C. Coupling between sagittal and frontal plane deformity correction in idiopathic thoracic scoliosis and its relationship with postoperative sagittal alignment. *Spine* **2010**, *35*, 1158–1164. [CrossRef]
19. Kwan, M.K.; Loh, K.W.; Chung, W.H.; Hasan, M.S.; Chan, C.Y.W. Perioperative outcome and complications following single-staged posterior spinal fusion using pedicle screw instrumentation in adolescent idiopathic scoliosis(AIS): A review of 1057 cases from a single centre. *BMC Musculoskelet. Disord.* **2021**, *22*, 413. [CrossRef] [PubMed]
20. Ferguson, J.; Hwang, S.W.; Tataryn, Z.; Samdani, A.F. Neuromonitoring changes in pediatric spinal deformity surgery: A single-institution experience. *J. Neurosurg. Pediatr.* **2014**, *13*, 247–254. [CrossRef]
21. Ozturk, C.; Karadereler, S.; Ornek, I.; Enercan, M.; Ganiyusufoglu, K.; Hamzaoglu, A. The role of routine magnetic resonance imaging in the preoperative evaluation of adolescent idiopathic scoliosis. *Int. Orthop.* **2010**, *34*, 543–546. [CrossRef]
22. Scaramuzzo, L.; Giudici, F.; Archetti, M.; Minoia, L.; Zagra, A.; Bongetta, D. Clinical relevance of preoperative MRI in adolescent idiopathic scoliosis: Is hydromyelia a predictive factor of intraoperative electrophysiological monitoring alterations? *Clin. Spine Surg.* **2019**, *32*, E183–E187. [CrossRef] [PubMed]
23. Chen, K.; Chen, Y.; Shao, J.; Zhoutian, J.; Wang, F.; Chen, Z.; Li, M. Long-Term Follow-up of Posterior Selective Thoracolumbar/Lumbar Fusion in Patients With Lenke 5C Adolescent Idiopathic Scoliosis: An Analysis of 10-Year Outcomes. *Glob. Spine J.* **2022**, *12*, 840–850. [CrossRef] [PubMed]

24. Ghandhari, H.; Ameri, E.; Nikouei, F.; Mahdavi, S.M.; Chehrassan, M.; Motalebi, M. Selective Thoracolumbar/Lumbar Fusion in Adolescent Idiopathic Scoliosis: A Comprehensive Review of the Literature. *Arch. Bone Jt. Surg.* **2023**, *11*, 313–320.
25. Pastorelli, F.; Di Silvestre, M.; Plasmati, R.; Michelucci, R.; Greggi, T.; Morigi, A.; Bacchin, M.R.; Bonarelli, S.; Cioni, A.; Vommaro, F.; et al. The prevention of neural complications in the surgical treatment of scoliosis: The role of the neurophysiological intraoperative monitoring. *Eur. Spine J.* **2011**, *20*, 105–114. [CrossRef] [PubMed]
26. Daroszewski, P.; Garasz, A.; Huber, J.; Kaczmarek, K.; Janusz, P.; Główka, P.; Tomaszewski, M.; Kotwicki, T. Update on neuromonitoring procedures applied during surgery of the spine—Observational study. *Reumatologia* **2023**, *61*, 21–29. [CrossRef] [PubMed]
27. Lenke, L.G.; Betz, R.R.; Harms, J.; Bridwell, K.H.; Clements, D.H.; Lowe, T.G.; Blanke, K. Adolescent idiopathic scoliosis: A new classification to determine extent of spinal arthrodesis. *J. Bone Jt. Surg.* **2001**, *83*, 1169–1181. [CrossRef]
28. MacDonald, D.B. Safety of intraoperative transcranial electrical stimulation motor evoked potential monitoring. *J. Clin. Neurophysiol.* **2002**, *19*, 416–429. [CrossRef]
29. Kaczmarek, A.M.; Huber, J.; Leszczyńska, K.; Wietrzak, P.; Kaczmarek, K. Relationships between the Clinical Test Results and Neurophysiological Findings in Patients with Thoracic Outlet Syndrome. *Bioengineering* **2022**, *9*, 598. [CrossRef] [PubMed]
30. Wesołek, A.; Daroszewski, P.; Huber, J. Neurophysiological Evaluation of the Functional State of Muscular and Nervous Systems in High-Maneuvering Jet Fighters. *Appl. Sci.* **2023**, *13*, 1120. [CrossRef]
31. Leszczyńska, K.; Huber, J. Unveiling the Correlations between Clinical Assessment of Spasticity and Muscle Strength and Neurophysiological Testing of Muscle Activity in Incomplete Spinal Cord Injury Patients: The Importance of a Comprehensive Evaluation. *Appl. Sci.* **2023**, *13*, 7609. [CrossRef]
32. Huber, J.; Leszczyńska, K.; Wincek, A.; Szymankiewicz-Szukała, A.; Fortuna, W.; Okurowski, S.; Tabakow, P. The Role of Peripheral Nerve Electrotherapy in Functional Recovery of Muscle Motor Units in Patients after Incomplete Spinal Cord Injury. *Appl. Sci.* **2021**, *11*, 9764. [CrossRef]
33. Wiertel-Krawczuk, A.; Huber, J.; Szymankiewicz-Szukała, A.; Wincek, A. Neurophysiological Evaluation of Neural Transmission in Brachial Plexus Motor Fibers with the Use of Magnetic versus Electrical Stimuli. *Sensors* **2023**, *23*, 4175. [CrossRef] [PubMed]
34. Wincek, A.; Huber, J.; Leszczyńska, K.; Fortuna, W.; Okurowski, S.; Chmielak, K.; Tabakow, P. The Long-Term Effect of Treatment Using the Transcranial Magnetic Stimulation rTMS in Patients after Incomplete Cervical or Thoracic Spinal Cord Injury. *J. Clin. Med.* **2021**, *10*, 2975. [CrossRef] [PubMed]
35. Leszczyńska, K.; Huber, J. Comparing Parameters of Motor Potentials Recordings Evoked Transcranially with Neuroimaging Results in Patients with Incomplete Spinal Cord Injury: Assessment and Diagnostic Capabilities. *Biomedicines* **2023**, *11*, 2602. [CrossRef] [PubMed]
36. Chang, S.H.; Park, Y.G.; Kim, D.H.; Yoon, S.Y. Monitoring of Motor and Somatosensory Evoked Potentials During Spine Surgery: Intraoperative Changes and Postoperative Outcomes. *Ann. Rehabil. Med.* **2016**, *40*, 470–480. [CrossRef] [PubMed]
37. Kimiskidis, V.K.; Potoupnis, M.; Papagiannopoulos, S.K.; Dimopoulos, G.; Kazis, D.A.; Markou, K.; Zara, F.; Kapetanos, G.; Kazis, A.D. Idiopathic scoliosis: A transcranial magnetic stimulation study. *J. Musculoskelet. Neuronal Interact.* **2007**, *7*, 155–160.
38. Lo, Y.L.; Dan, Y.F.; Tan, Y.E.; Tan, C.T.; Raman, S. Intra-operative monitoring in scoliosis surgery with multi-pulse cortical stimuli and desflurane anesthesia. *Spinal Cord* **2004**, *42*, 342–345. [CrossRef] [PubMed]
39. Edmonds, H.L.; Paloheimo, M.P., Jr.; Backman, M.H.; Johnson, J.R.; Holt, R.T.; Shields, C.B. Transcranial magnetic motor evoked potentials (tcMMEP) for functional monitoring of motor pathways during scoliosis surgery. *Spine* **1989**, *14*, 683–686. [CrossRef] [PubMed]
40. Gadella, M.C.; Dulfer, S.E.; Absalom, A.R.; Lange, F.; Scholtens-Henzen, C.H.; Groen, R.J.; Wapstra, F.H.; Faber, C.; Tamási, K.; Sahinovic, M.M.; et al. Comparing Motor-Evoked Potential Characteristics of Needle versus Surface Recording Electrodes during Spinal Cord Monitoring-The NERFACE Study Part I. *J. Clin. Med.* **2023**, *12*, 1404. [CrossRef]
41. Dulfer, S.E.; Gadella, M.C.; Tamási, K.; Absalom, A.R.; Lange, F.; Scholtens-Henzen, C.H.; Faber, C.; Wapstra, F.H.; Groen, R.J.; Sahinovic, M.M.; et al. Use of Needle Versus Surface Recording Electrodes for Detection of Intraoperative Motor Warnings: A Non-Inferiority Trial. The NERFACE Study Part II. *J. Clin. Med.* **2023**, *12*, 1753. [CrossRef] [PubMed]