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ORIGINAL ARTICLE

USEFULNESS OF THE SURFACE ELECTROMYOGRAPHICAL RECORDINGS FOR EVALUATION OF SYNERGISTIC MUSCLE FUNCTION IN THE LOWER EXTREMITIES OF PATIENTS AFTER INCOMPLETE SPINAL CORD INJURIES FOR THE PHYSIOTHERAPY PURPOSES

PRZYDATNOŚĆ REJESTRACJI ELEKTROMIOGRAFICZNYCH METODĄ POWIERZCHNIOWĄ DO OCENY FUNKCJI MIĘŚNI SYNERGISTYCZNYCH KOŃCZYN DOLNYCH U PACJENTÓW PO NIECAŁKOWITYCH URAZACH RDZENIA KRĘGOWEGO DLA CELÓW FIZJOTERAPII

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ABSTRACT

Introduction

Electromyographic examinations with the use of surface leads (sEMG) in the standing and lying position are used in the diagnosis of musculoskeletal disorders and prognostically, assessing the patient's therapeutic process, especially kinesiotherapy. There is little data on synergistic muscle function in patients with partial spinal cord injury (iSCI) from which an optimal isometric rehabilitation program can be determined.

Aim

The aim of the following pilot study is to demonstrate the pathological pattern of synergistic interaction of lower limb muscles in patients with (iSCI) preventing correct posture. This is to enable the future to create a detailed algorithm through selective and targeted activities aimed at restoring the correct pattern of muscle synergy.

Material and methods

The studies were carried out in 12 patients with (iSCI) (documented in the MRI at levels C3-C8 and Th7-S1). The electrodes recorded bipolar activity (sEMG) on both sides of the: gluteus maximus (GM), rectus femoris (RF), tibialis anterior (TIB), extensors of the back of the foot (EXT). Records were performed in the position that activated the proximal and distal muscles.

Results

The results show changes in the muscle synergy pattern for the lower extremities in patients with (iSCI), by the intensification of muscle interaction (GM) with (EXT).

Conclusions

The results demonstrate the behavior of the synergistic muscle pathways of the distal muscles of the lower extremities and the role of the interacting with (GM) activity in maintaining correct posture. Kinesiotherapy exercises should be aimed at returning balance between (RE) and (GM) to restore the patient's correct posture.

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Keywords: incomplete spinal cord injury, synergistic muscles, lower extremity, physiotherapy

STRESZCZENIE

Wstęp

Badania elektromiograficzne z wykorzystaniem odprowadzeń powierzchniowych (sEMG) w pozycji stojącej oraz leżącej są wykorzystywane zarówno w diagnostyce schorzeń narządu ruchu oraz prognostycznie, oceniając proces leczniczy pacjenta, zwłaszcza kinezyterapii. Istnieje mało danych na temat wzorca czynności mięśni synergistycznych u chorych po częściowych urazach rdzenia (iSCI), na podstawie których można by ustalić optymalny program ćwiczeń izometrycznych usprawniających.

Cel

Celem poniższego badania pilotażowego jest wykazanie patologicznego wzorca współdziałania mięśni synergistycznych kończyn dolnych u pacjentów z (iSCI) uniemożliwiających prawidłową postawę. Umożliwi to w przyszłości stworzenie algorytmu usprawniającego, poprzez selektywne i celowane działania dążące do odtworzenia prawidłowego wzorca synergii mięśniowych.

Materiał i metody

Badania pilotażowe przeprowadzono u 12 chorych leczonych z powodu niecałkowitego urazu rdzenia kręgowego, udokumentowanego w obrazie MRI, na poziomach C3-C8 i Th7-S1. Elektrodami powierzchniowymi (sEMG) rejestrowano obustronnie czynność polielektromiograficzną z mięśni pośladkowych (GM), prostych uda (RF), piszczelowych przednich (TIB), prostowników grzbietu stopy (EXT). Przeprowadzono rejestracje w pozycjach stojącej oraz aktywizujących mięśnie proksymalne i dystalne działające synergistycznie. Parametrem wyjściowym testów sEMG była średnia wartość amplitudy mierzona w mikrowoltach.

Wyniki

Wyniki wykazują obecność zmiany wzorca synergii mięśniowych kończyn dolnych u pacjentów z niecałkowitym uszkodzeniem rdzenia kręgowego, polegającą na nasileniu współdziałania mięśni GM oraz EXT.

Wnioski

Wyniki wykazują zarówno częściowe zachowanie czynności synergistycznych grup mięśniowych w części proksymalnej i dystalnej kończyn dolnych, oraz rolę mięśni dystalnych kończyn dolnych we współdziałaniu z aktywnością mięśnia GM w utrzymaniu prawidłowej postawy u chorych z iSCI. Ćwiczenia kinezyterapeutyczne powinny być ukierunkowane na wyrównanie utraconego balansu pomiędzy GM i RF, przyczyniając się do odtwórczości postawy chorego z iSCI.

Słowa kluczowe: niecałkowite uszkodzenie rdzenia kręgowego, mięśnie synergistyczne, kończyna dolna, fizjoterapia

Introduction

The electromyography (EMG) method, both tested during the maximal contraction and in the standing position, is currently used by both physiotherapists and orthopedists as a diagnostic tool as well as the prognostic in the evaluation of treatment efficiency. Previous studies in lower extremities muscles in case of incomplete spinal cord injury (iSCI) focused mainly on the assessment of spasticity, paralysis and the efficiency of muscle motor units in the context of a kinesiotherapy application. An additional aspect is a possibility of determining the function of the synergistic muscles, which is referred to as the muscle synergism. As a result, it is possible to identify the functional and individual patient's movement pattern and to compare it with patterns existing in a population of healthy people.

The term muscle synergism means the presence of co-contractions that are independent of our will and activated during the ankle movement, they increase with the mechanical stiffness of the ankle joint (*Balbinot et al. 2021*). Unfortunately, increasing this stiffness negatively affects the balance of posture. Among patients with incomplete spinal cord injury one can observe the increasing number of co-contractions. This relationship is a form of compensation for the disturbing movement coordination. The researchers (*Chan et al. 2021*) demonstrated muscle synergism between soleus (SOL) and medial gastrocnemius (MG) as the main muscles responsible for plantar flexion of the ankle joint, while tibialis anterior (TA) was defined as the main muscle responsible for dorsiflexion. In the mentioned study, it was observed that patients after iSCI are characterized by increased TA activity, which was previously observed in the elderly (*Benjuya et al. 2004; Bean et al. 2003; Abe et al. 2017*). At the same time, they indicate that in younger people this phenomenon is rarely active during quiet standing (TA) (*Kawashima et al. 2008; Joseph et al. 1955*). A different look at muscle synergism is presented by movement neuroscience, according to which individual muscles are organized into functional groups (*Clark et al. 2010*). Another interesting concept of synergy is the so-called synchronous synergy, the assumption of which is based on the fact that the muscle conglomerates are activated in order to perform a motor task. It assumes that each activation of synergy will stimulate all the muscles that make up its composition (*Jarc and Tresch 2009*). In order to study muscle synergy in patients after iSCI, an interesting proposition seems to be a test performed while riding a stationary bike (*Barroso et al. 2015*). It has been found that the examined muscles of the lower extremities show the same muscle synergism during cycling as in the case of walking (*Barroso et al. 2015*). The authors of the above study indicate the presence of serious sensorimotor disorders in patients with iSCI, such as pathological patterns of locomotion and spasticity (*Aleixandre et al. 2014*). Moreover, it was possible to confirm the fact that patients manifesting a smaller functional deficit had a more similar pattern of muscle synergism in relation to the normative values (*Castellano et al. 2003*).

Three main muscle synergies have been demonstrated:

- synergy I – gluteus medius, adductor longus, sartorius, tibialis anterior and rectus femoris muscles – in lower extremity flexion movement,
- synergy II – tensor facia latae, vastus lateralis, vastus medialis, and to a reduced extent TA and RF muscles – during the final phase of flexion and the beginning of lower extremity extension,
- synergy III – biceps femoris, semitendinosus, gastrocnemius lateralis, gastrocnemius medialis – during the extension movement of the lower extremity.

An additional, important observation is the fact that post-iSCI subjects had an earlier moment of muscle activation compared to healthy subjects. Researchers confirm that patients with incomplete spinal injury retain synergistic muscle control. A correlation has been demonstrated between the observed muscle synergies and the motor performance of patients and the level of spasticity they represented. In addition, it was noted that taking into account the entire group of patients with iSCI, the activation factor parameter turned out to be more similar to healthy people, and not the muscle synergy vector.

So far, the currently available studies have not described the patterns of muscle synergy occurring in patients with iSCI recorded with sEMG (*Chan et al. 2021, Barroso et al. 2015; Holmes et al. 2004*). At present, no one has described the global pattern of lower extremities muscle synergy in patients with iSCI. When extending the search to include phrases such as: "...for prognostic purposes, for physiotherapeutic purposes, or as a further prognostic of treatment," the results were negative. As a result of the spinal injury, the continuity of neural connections between the supraspinal centers and the spinal cord centers are interrupted. A direct consequence of the above is a change in the synergistic pattern of muscle action below the level of injury. Thanks to EMG tests, it is possible to determine the individual iSCI patient's pattern of the muscle's synergy, and after comparison with the normative values, to create a targeted algorithm for kinesiotherapy.

Aim

The aim of the presented pilot study is to demonstrate a pathological pattern of interaction of the synergistic muscles in the lower extremities in patients after iSCI. The choice of the sEMG method as a diagnostic tool is intentional according to the statement of Holmes *et al.* (2004).

Material and methods

Surface polyelectromyography (sEMG) was performed with a 4-channel Keypoint System (Medtronic A/S, Skovlunde, Denmark), according to the Guidelines of the International Federation of Clinical Neurophysiology – European Chapter; every test was performed under the supervision of certified personnel for clinical neurophysiological testing.

The research scheme consisted of two main parts, sEMG recordings from the chosen muscles of lower extremities in their proximal and distal parts were performed in lying and standing, if the patient was able to maintain an upright position. Bilateral recordings comprised gluteus maximus (GM), rectus femoris (RF), tibialis anterior (TA) and extensor digitorum brevis (EXT) muscles. The above-mentioned muscle groups were tested under the conditions of muscle relaxation and during the test of maximal contraction lasting five seconds. The maximal contraction test consisted of simultaneous bilateral contraction of GM and RF on demand ("tight the buttocks, straight legs at the knees slightly up"), and then activation of TA and EXT muscle groups by "pulling the foot and toes towards the face" of the patient.

The above test was also carried out in a standing position – if it was possible. The patient stood on a plexiglas plate 50 cm × 30 cm. First, the muscle activity was monitored while standing relaxed, and then the exercise test was performed. In order to activate the above-mentioned muscle groups, the following tests were recommended – "stand at attention" – activation of GM and RF, "stand on your heels and pull your toes towards your face" – activation (TA) and (EXT).

The flow chart in Figure 1 presents the principles of the study design. The final study group consisted of 12 men (aged from 11 to 68 years, weighing from 48 to 94 kilograms, the average BMI = 27.8) with incomplete spinal cord injury (Figure 2) who were treated at the Department of Neurosurgery in Wrocław University of Medical Sciences and at Akson Rehabilitation Center in Wrocław, Poland. All of them underwent physical therapy and intensive kinesiotherapy. They spent on average 10.4 hours a day in a supine position, on average 8.2 hours in a sitting position. The inclusion criterion was the written consent to have performed EMG tests of a non-invasive nature. The basic aspect of including a patient in the study group was the magnetic resonance imaging confirming incomplete spinal injury, with the preserved at the level of injury at least 1/3 of the structures in the cross-section.

Patients were diagnosed at the request of the attending physician at the EMG and ENG Diagnostic Unit located at the Wiktor Dega Orthopedic and Rehabilitation Clinical

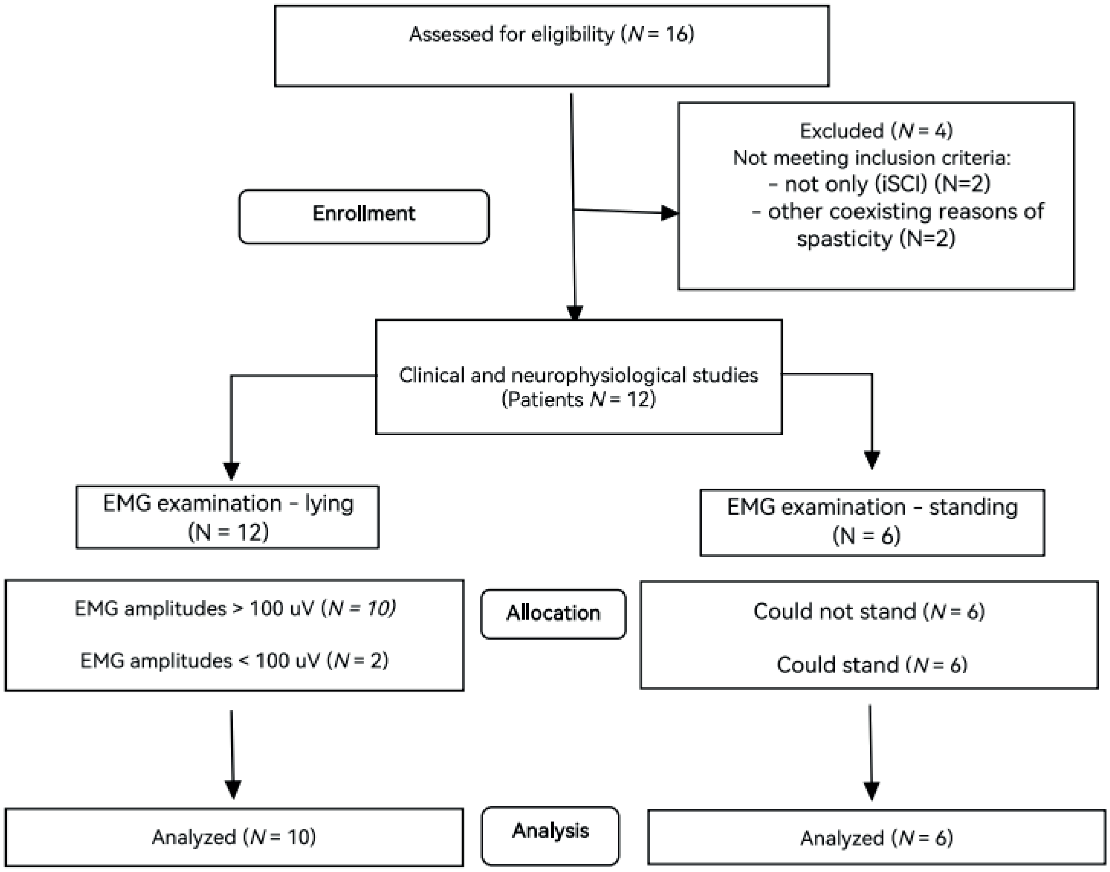

Figure 1. Flow chat of the study

Hospital in Poznań, Poland. The Bioethical Committee of University of Medical Sciences in Poznań, Poland confirmed to conduct the study with the decision no. 559/2018. The studies were performed in agreement with the Declaration of Helsinki.

the reference electrode was placed on its distal tendon. The ground electrode was located in the distal part of the leg. Commonly, the Key Point recorder's upper 10kHz and lower 20Hz filters were set. Recordings were made at the time base of 80ms/D and amplified in

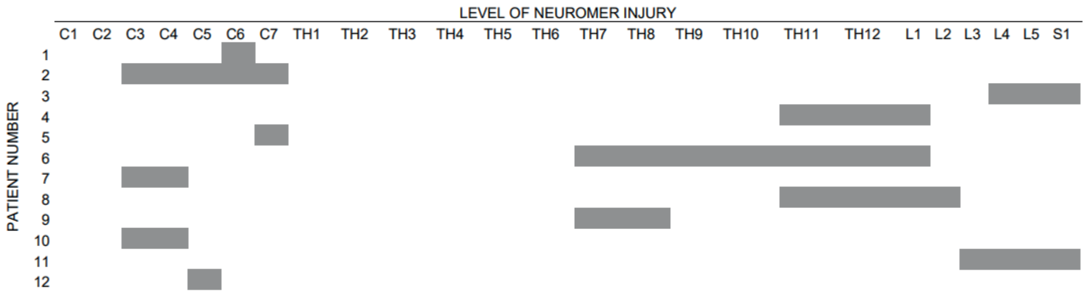

Figure 2. iSCI injury compartment

sEMG activity was recorded bilaterally with surface disposable Ag/AgCl electrodes. The active surface of each there was 5mm². sEMG recordings were performed with an active electrode placed on the muscle's belly, while

a range 20–1000 μV/D. The average amplitude parameters (minimum–maximum, the peak-to-peak of recruiting motor unit action potential deflection regarding the isoelectric line, measured in μV) were analyzed. During performing sEMG studies, the neurophysiologist verbally instructed first to keep calm and relax muscles for 5 seconds, then encouraged the subjects to make three attempts at the muscle's maximal contraction. Participants were instructed to contract the tested muscle as hard and fast as possible until the neurophysiologist requested them to finish the attempt. The test was conducted three times, with a 1 minute resting period between each muscle contraction. Methodological guidelines and more principles of sEMG recordings analysis are described in studies by Lisiński *et al.* (2014) and Lisiński and Huber (2017). If the recorded sEMG amplitude under resting condition did not exceed 20–25 μV, it proved the presence of normal muscle tone, if more – the increased muscle tension. Amplitudes of sEMG during the attempt of maximal contraction not exceeding 600 μV suggested pathological activity of motor units. The records with the highest amplitude (in μV) and frequency (not more than 90 Hz) were used for the analysis.

Statistical data were calculated with Statistica 13.3 software (StatSoft, Kraków, Poland). Descriptive statistics included minimal and maximal values (range), mean and standard deviations (SD) for measurable values. The results from all neurophysiological tests were compared to the normative data recorded in the Department of Pathophysiology of Locomotor Organs of the University of Medical Sciences in Poznań, Poland. Because of the pilot character of the study and the low number of participants, the parameters of sEMG were analysed between the right and left sides and simply compared as dependent groups with a dependent T-Student test, for data currently recorded and analogical in healthy volunteers (*Lisiński et al. 2014*). P-values of less than 0.05 were considered to be statistically significant.

Results

Examples of original sEMG recordings during standing and lying positions following the attempt of maximal contractions are presented in Figure 3 while their parameters of mean amplitudes are summarized in tables and histograms below.

Data in Table 1 show that analyzed parameters of amplitudes in sEMG during standing and lying recorded on the right side in comparison to the left side did not differ significantly in iSCI patients. On the other hand, the values of amplitudes at rest during lying recorded in iSCI patients significantly exceeded the mean value of 25 μV recorded in healthy subjects at $p = 0.04$, which convinced about the increased muscle tension. Cumulative mean values of amplitudes of sEMG recordings during standing and lying during the attempt of maximal contraction and relaxation during standing also did not differ significantly from those evaluated in the healthy population. Differences appear when amplitudes in sEMG recorded in the last three mentioned conditions are considered separately for certain muscle groups.

Interestingly, one should expect that the partial cutting off the neural transmission from the upper motor neuron to its destination control located below the level at which the injury occurred should result in an imbalance of synergy between the synergistic muscles acting in the proximal and distal parts of the lower extremities. The synergies between GM and RF as well as the TA and EXT have been detected, but in a lower frequency than in the subjects of the healthy population, more in standing (Table 2, $p = 0.004$) than in lying (Table 3, $p = 0.05$). It has been observed the increased frequency of synergistic actions between GM and EXT during standing, significantly differed from those observed in a healthy population at $p = 0.004$.

The synergistic pattern of actions during standing between TA and EXT has been observed to be similar both at rest (Figure 4) and during contraction (Figure 5). As for the relationship between GM and RF activity, it has changed at $p = 0.05$ with the reference to the healthy population, which is the evidence of a change in the muscle synergy pattern.

The observations from the tests in the supine position confirm the partial preservation of

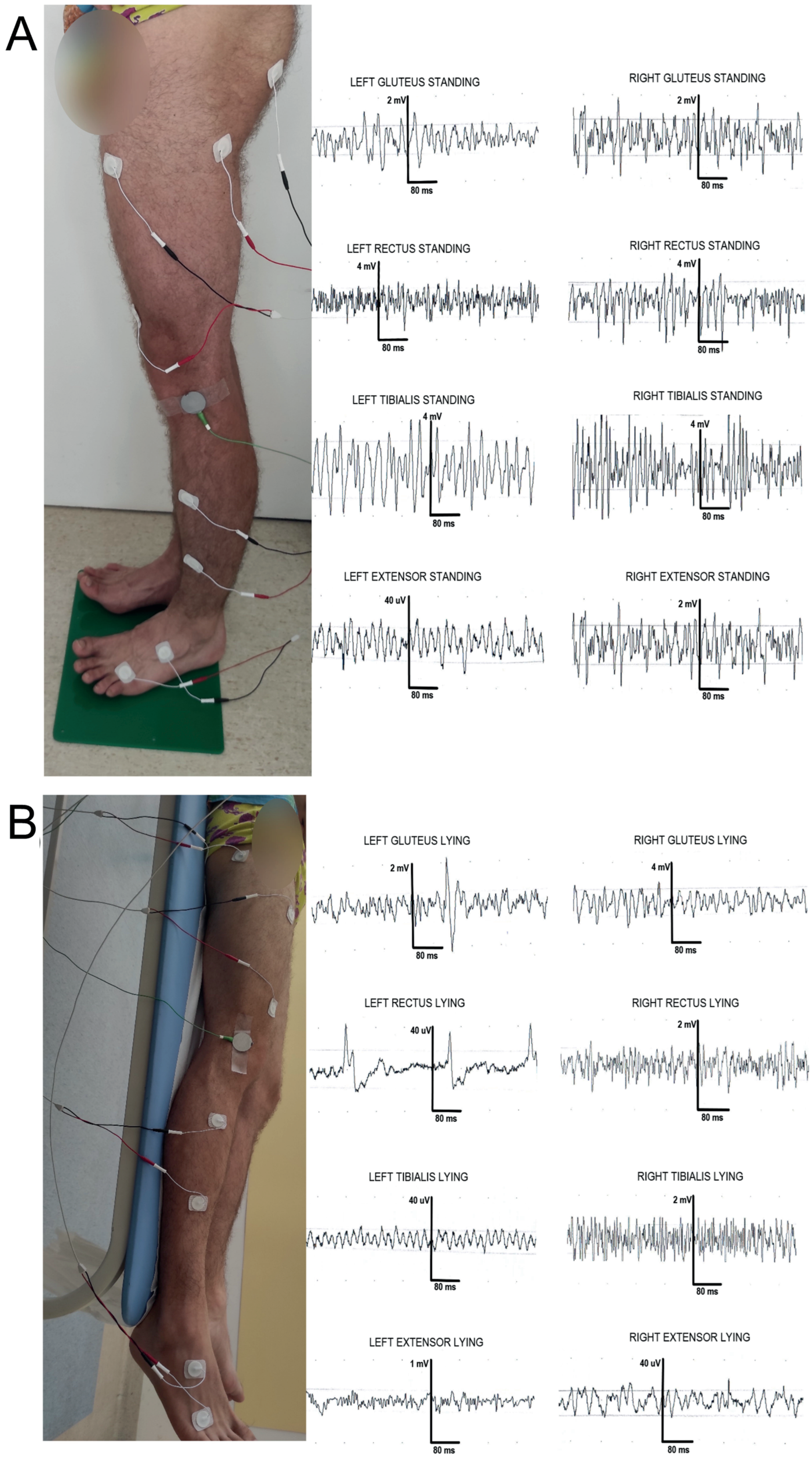

Figure 3. A – Examples of sEMG recordings from proximal and distal muscles in lower extremities during maximal contraction in a standing position; B – examples of sEMG recordings with the same positions of electrodes as in A during maximal contraction in a lying position

Table 1. Average values of sEMG amplitudes (in μV) recorded from the tested muscles in a group of iSCI patients.

Body side / recording condition	Left	Right	P
Resting state during lying	54	46.2	P = 0.05
Contraction during lying	1152.8	1180.9	P = 0.06
Standing at rest	92.5	89.9	P = 0.06
Contraction during standing	1745.1	1771.8	P = 0.06

Table 2. The number of co-existing muscles synergies during standing.

Muscles	Gluteus	Rectus	Tibialis	Extensor
Gluteus	x	x	x	x
Rectus	10/12	x	x	x
Tibialis	10/12	12/12	X	x
Extensor	9/12	12/12	12/12	x

Abbreviation: x – no synergy

Table 3. The number of co-existing muscles synergies during lying.

Muscles	Gluteus	Rectus	Tibialis	Extensor
Gluteus	x	x	x	x
Rectus	18/20	x	x	x
Tibialis	16/20	17/20	x	x
Extensor	17/20	18/20	17/20	x

Abbreviation: x – no synergy

Figure 4. Amplitudes of sEMG recordings from the lower extremities at rest in a standing position

muscle synergism in iSCI patients. There is a correlation between the muscle synergy pattern for TA and EXT at rest (Figure 6) and during the contraction (Figure 7). There has not been detected such a strict relationship between activation of GM and RF, which proves the change in the muscle synergy pattern in comparison to the healthy population it is different at p = 0.005.

Discussion

In this pilot study, the results confirm the presence of slightly changed but preserved muscle synergies and synergistic muscle

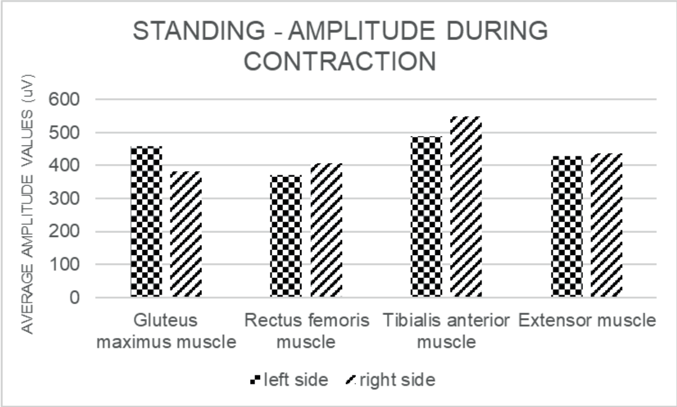

Figure 5. Amplitudes of sEMG recording from lower extremities muscles during the maximal contraction in standing position

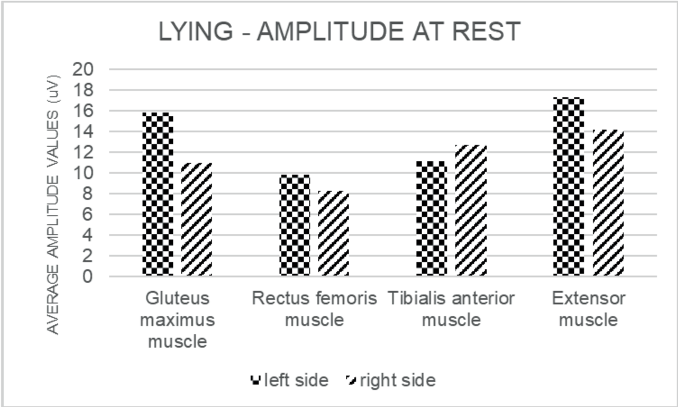

Figure 6. Amplitudes of the sEMG recordings at rest during lying position

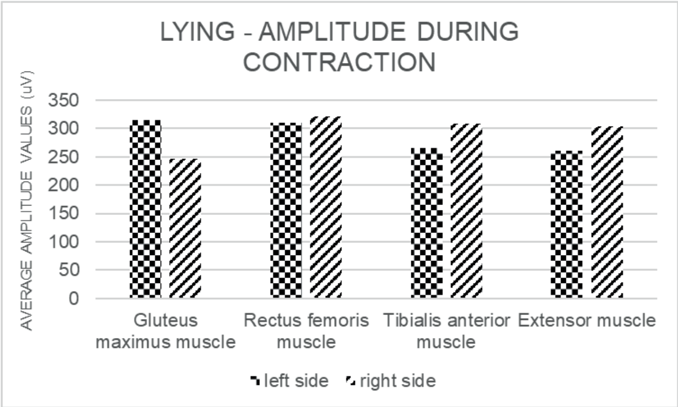

Figure 7. Amplitudes of the sEMG recordings during maximal contraction in a lying position

control, despite iSCI. They clearly confirm the conclusions of the studies by Jarc *et al.* (2009) and Castellano *et al.* (2003). Moreover, it was possible to observe, that iSCI patients representing moderate functional deficits could have recorded sEMG with the values of parameters such as amplitude and activation frequency close to the normative values. An interesting observation is a fact, that in the studied group only few patients showed a slightly (more than 30 μV) increased muscle tension in one of the examined muscles. This is surprising because, according to the results of the study by Barroso *et al.* (2015), most iSCI patients should present symptoms of sensorimotor disorders, such as increased muscle tension, clinically evaluated as spasticity, which has not been commonly observed in our study group.

One of the most relevant findings in the presented study is the relationship (high incidence of co-excitation) between GM and RF activity, it differed at $p = 0.05$ with reference to the healthy population which is the evidence for a change in the synergy pattern of proximal-distal lower extremities muscles in iSCI patients. This observation, however, should be confirmed in the larger samples of sEMG recordings performed in iSCI patients, which low number is the main limitation of this study, enabling more precise statistical analysis. The second limitation is the wide compartment of iSCI injuries at different spinal levels, a more homogenous population of patients is necessary for future studies.

So far only the work of Lisiński *et al.* (2014) presented a similar description of synergistic muscle activity studies in normal standing among the population of healthy subjects.

Conclusions

Our study demonstrates the direct usefulness of the sEMG method in order to obtain detailed data on the muscle synergies in the lower extremities of iSCI patients. An unexpected synergy relationship between the activity of GM and EXT muscles has been demonstrated in iSCI patients which implies that kinesiotherapy exercise should be targeted for recovery of the balance between RF and GM to restore the patient's correct posture.

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