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ORIGINAL ARTICLE

CAN MOTOR-EVOKED POTENTIAL STUDIES BE UTILIZED FOR THE EVALUATION OF NEURAL TRANSMISSION IN THE PROPRIOSPINAL FIBERS OF THE HUMAN SPINAL CORD? PILOT STUDY

CZY BADANIE POTENCJAŁÓW RUCHOWYCH WYWOŁANYCH POLEM MAGNETYCZNYM MOŻE SŁUŻYĆ DO OKREŚLENIA PRZEWODNICTWA NEURONÓW PROPRIOSPINALNYCH W SZLAKACH RDZENIA KRĘGOWEGO U CZŁOWIEKA? BADANIE PILOTAŻOWE

Jędrzej Pepliński[1], Matylda Witkowska[1], Miłosz Tchórzka[1], Kinga Dudek[1], Ryszard Śliwiński[1], Ewa Gajewska[2], Magdalena Sobieska[3], Juliusz Huber[1]

[1]Department of Pathophysiology of Locomotor Organs, University of Medical Sciences in Poznan, Poland

[2]Department and Clinic of Developmental Neurology, University of Medical Sciences in Poznan, Poland

[3]Department of Physiotherapy, University of Medical Sciences in Poznan, Poland

ABSTRACT

Introduction

Many modern physiotherapeutic techniques using neurophysiological mechanisms are based on the propriospinal neurons system (PNS) activity responsible for the reflex control of locomotion. Stimulation of proprioceptors by the kinesiotherapist determines the initiation of therapy, different manual skills can be replaced with a unified, calibrated electric or magnetic stimulus.

Aim

The aim of the study was to check whether stimulation using the motor evoked potentials (MEP) method can be used to verify the activation of the propriospinal system and as a source of stimulus in kinesiotherapy using the Vojta method.

Material and methods

The study included 26 healthy subjects who underwent the magnetic stimulation at the acromion (ACR) on the left side and transvertebrally at C3-C4 levels. The MEPs were recorded from the biceps brachii (BB) and rectus femoris (RF) muscles using the surface electrodes (sEMG).

Results

Parameters of 52 MEPs potentials recorded from BB bilaterally and 30 recorded from RF were analysed. Based on their frequency value, the sequence of muscles activation was calculated, which with stimulation from left ACR as well as at C3-C4 levels in a midline was as follows: left BB, right BB, right RF and left RF. Latencies of potentials after ACR stimulations were shorter in recordings from both BB and RF muscles than following the stimulation at C3-C4 level.

Conclusions

Different fractions of the fibers in the long cervico-lumbar propriospinal system are activated following the magnetic stimulus applied at ACR via the afferent connections or only at C3-C4 cells of origin. However, they both transmit the neural signals in a velocity range characteristic for the propriospinal system.

Keywords: neurophysiological studies, motor evoked potentials, propriospinal neurons, spinal cord reflex pathways, physiotherapy

STRESZCZENIE

Wstęp

Wiele współczesnych technik fizjoterapeutycznych wykorzystujących mechanizmy neurofizjologiczne opiera się na działaniu układu neuronów propriospinalnych (PNS) odpowiedzialnych za odruchową kontrolę lokomocji. Pobudzenie proprioceptorów przez kinezjoterapeutę warunkuje rozpoczęcie terapii, zróżnicowane umiejętności manualne można zastąpić stosowaniem jednolitego, skalibrowanego bodźca elektrycznego lub magnetycznego.

Cel pracy

Celem pracy było sprawdzenie, czy stymulacja w metodzie ruchowych potencjałów wywołanych (MEP) może być stosowana do weryfikacji pobudzenia układu propriospinalnego oraz jako źródło bodźca w kinezyterapii metodą Vojty.

Materiał i metody

Badaniami objęto 26 zdrowych osób, u których wykonano stymulację magnetyczną w okolicy wyrostka barkowego (ACR) strony lewej oraz przezkręgowo na poziomie C3-C4. MEP rejestrowano z mięśnia dwugłowego ramienia (BB) i prostego uda (RF) obustronnie z wykorzystaniem elektrod powierzchniowych (sEMG).

Wyniki

Przeanalizowano parametry 52 potencjałów MEP obustronnie zarejestrowanych z BB i 30 zarejestrowanych z RF. Na podstawie wartości ich częstotliwości obliczono sekwencję aktywacji mięśni, która przy stymulacji lewego ACR oraz na poziomach C3-C4 w linii środkowej przedstawiała się następująco: lewy BB, prawy BB, prawy RF i lewy RF. Opóźnienia rejestrowanych potencjałów po stymulacji ACR były krótsze przy odprowadzeniach zarówno z mięśni BB, jak i RF, niż po stymulacji na poziomie C3-C4.

Wnioski

Różne frakcje włókien układu propriospinalnego szyjno-lędźwiowego ulegają aktywacji pod wpływem bodźców magnetycznych zastosowanych w ACR poprzez połączenia czuciowe lub tylko w komórkach początkowych C3-C4. Obydwa jednak przekazują pobudzenia neuronalne w zakresie prędkości charakterystycznym dla układu propriospinalnego.

Słowa kluczowe: badania neurofizjologiczne, ruchowe potencjały wywołane, neurony propriospinalne, szlaki odruchowe rdzenia kręgowego, fizjoterapia

Author responsible for correspondence:
Matylda Witkowska
Department of Pathophysiology of Locomotor Organs
Karol Marcinkowski University of Medical Sciences
28 Czerwca 1956 No 135/147
61-545 Poznań, Poland
Email: matylda.wit@gmail.com
https://orcid.org/0009-0004-3016-4927

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Introduction

The mechanism of action of the proprioceptive neuromuscular facilitation (PNF) method or Vojta therapy is based on the principle of spinal cord reflexes coordination (Gajewska *et al.,* 2018). The latter aims to restore the basic locomotor movement patterns. By stimulating specific anatomical points, the rhythmic activation of skeletal muscles and the central nervous system centers are driven. Although their effectiveness as therapeutic methods in physiotherapy has been proven in various diseases of the musculoskeletal system, the mechanism of action has not been fully explained. Originally, their anatomical basis is associated with the presence in the spinal cord of a system of descending and ascending fibers with cells of origin in the cervical and lumbar spinal cord, having crossed axons at the level of Th8-Th10, called propriospinal neurons. They were described by Sherrington and Leslett (1903), and proven as playing an important role in conducting neuronal signals and coordinating motor circuits, as well as controlling reflexes within the spinal cord. Vojta therapy is based on reflex locomotion and aims to restore basic movement patterns (Cote *et al.* 2018). Its origins date back to 1954, and the first reactions were elicited by pressure on specific anatomical points, in the supine, prone and crawling positions (Vojta, 1965; Vojta and Peters, 2007). Vojta therapy is used extensively in physiotherapy to treat neurological patients, particularly children (De-La-Barrera-Aranda *et al.*, 2021). The possible transmission pathways of nerve impulses that stimulate muscles in the upper and lower limbs during Vojta therapy, are not completely confirmed (Gajewska *et al.*, 2018). The kinesiotherapist's ability to properly conduct both Vojta and PNF therapy depends on skills, especially in the application of afferent stimuli (resistance, movement tracking, pressure), the purpose of which is to drive the spinal neuronal motor centers. It can be supposed, that applying the unified, calibrated electric or magnetic stimulus exciting the proprioceptors might increase the properness and effectiveness of the therapies. Such attempts to find a unified stimulus have not been done before. An interesting proposal might be to use the magnetic stimulus as a part of the motor evoked potentials (MEP) methodology which is commonly utilized in the neurophysiological diagnostic. Its effectiveness and non-invasiveness were proven in many reports on the diagnostic of locomotor system disorders (Leszczyńska and Huber, 2023b). The review of the literature did not provide data on the utilizing the MEPs studies for investigation of the propriospinal neurones activity. One of the neurophysiological methods to indirectly study propriospinal connections in humans has appeared to be polyelectromyography (pEMG) (Gajewska *et al.* 2018). This study aims to verify if the stimulation in the motor evoked potentials (MEPs) methodology used to verify the excitation of propriospinal system, might have been used for the Vojta kinesiotherapy procedure, simultaneously. We applied the magnetic stimuli at acromion, directly at the same place as it is originally described in this therapy methodology. It aimed to excite the afferent system carrying the neuronal signals from the proprioceptors and drive the cells of origin of long propriospinal fibers at C3-C4. To compare the expected excitatory effects at acromion, the C3-C4 spinal centers have been directly induced with the magnetic stimuli, as well.

Materials and methods

We have performed tests on 26 healthy subjects aged 21-25 years and 165-186 cm tall, 172.6 cm on average. During the clinical evaluation, any of the subjects had revealed any signs of increased muscle tension or any other symptom of the muscles dysfunction. This section outlines the methodological principles of bilateral surface electromyography (sEMG) used to record the motor evoked potentials (MEP) with the bipolar surface electrodes (Figure 1). We decided to choose the proximal muscles of upper and lower extremities bilaterally (Figure 1 A and B) for sEMG recordings similarly as in the study of Gajewska et al. (2018).

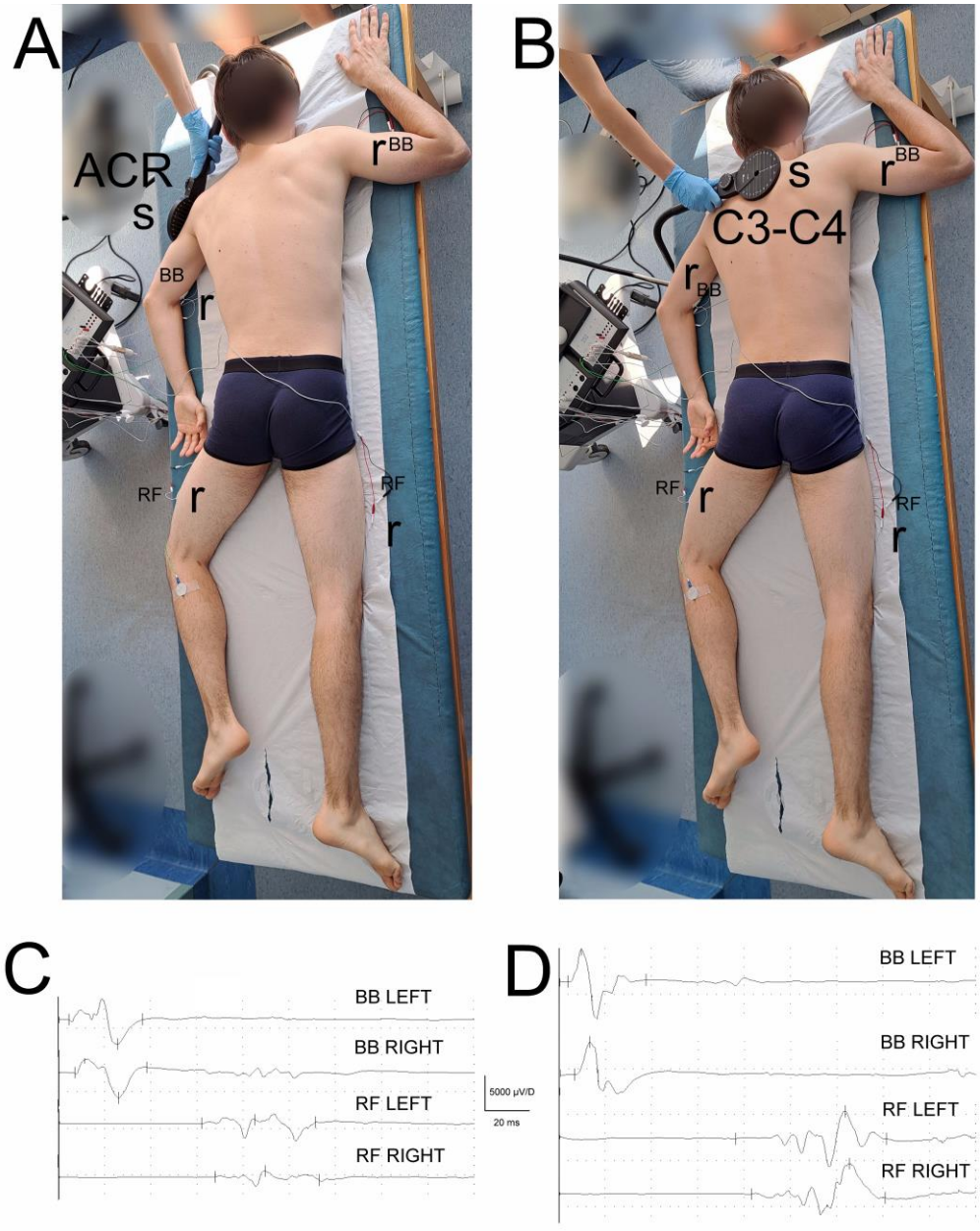

Figure 1. Photographs of the bilateral location of sEMG recording electrodes (r) over the muscles on the body of the examined subject during magnetic stimulation (s) on the acromion (A) or transvertebrally at C3-C4 cervical level (B) in the midline. The photo in A shows the position of the coil triggering the magnetic field pulse, corresponding to the stimulation used by the kinesiotherapist during the application of Vojta therapy. Examples of the recordings the evoked potentials

recorded from biceps brachii (BB) and rectus femoris (RF) bilaterally, following the magnetic excitation with a single stimulus applied at acromion (C, ACR) or transvertebrally at C3-C4 (D, C3-C4).

Subjects were lying in a prone position with their arms abducted at glenohumeral joint to 90° and flexed at elbows to 90°, and left leg bend at hip joint to 30° and flexed at knee to 90°, right leg remained straight. We placed electrodes on muscles of upper extremity and lower extremities, accordingly at biceps brachii (BB) and rectus femoris (RF) on both sides. We measured distances from electrodes to the relevant stimulated spinal cord level at C3-C4 for upper extremities, the lumbosacral level (LS) for lower extremities, as well as distances from C3-C4 level to the LS of the spine. The sEMG recordings were performed using the KeyPoint Diagnostic System (Medtronic A/S, Skøvlunde, Denmark).

Study was performed in an air-conditioned room with an average temperature of 22°C. For sEMG measurements, we applied standard, disposable Ag/AgCl surface recording electrodes with 5 mm^2 of an active surface. Cathode was placed on the muscle belly, and anode was placed on the distal tendon of the same muscle; the ground electrode was placed on the proximal part of the upper extremity and the distal part of the lower extremity according to the Guidelines of the International Federation of Clinical Neurophysiology —European Chapter (Stålberg *et al.*, 2019; see also Kaczmarek *et al.*, 2022). We set the upper 10 kHz and the lower 20 Hz filters in the recorder. The sEMG recordings had two parts. Firstly we magnetically stimulated acromion (ACR) on the left side and later stimulated neurons of origin of the propriospinal descending tracts exiting in the spinal cord at C3-C4 vertebral levels. The stimulation was performed at each point twice with the rest period of 1 minute. The best attempt was kept, the one with the highest mean amplitude measured from peak-to-peak and the shortest latency parameters with reference to the isoelectric line. The output measurements from MEP recordings was the amplitude in μV, the latency in ms, and the conduction velocities of the neural transmission in m/s. Recordings were performed at a base time of 20 ms/D and an amplification of 1000-5000 μV/D (Figure 1 C, D) (Leszczyńska and Huber, 2023b). Transcranial magnetic stimulation (TMS) is a method of excitation with the stimulus to the nervous system structures which penetrates through a bone and soft tissue. TMS is used in diagnostics to produce motor evoked potentials (MEP) to test the functional integrity of the spinal cord structures transmitting the neural signals (Wincek *et al.,* 2021). By stimulating the motor center, it is possible to verify that the impulse evoked in the spinal centers is carried correctly through the spinal tracts and reaches the peripheral nerves as well as the corresponding effectors. The device we used for the generation of the magnetic stimulus, both for therapeutic and diagnostic purposes, was MagPro R30 and MagPro X100 magnetic stimulator with MagOption (Medtronic A/S, Skøvlunde, Denmark) (Figure 1 A and B). Each patient may have different MEP recording parameters because of the minimal stimulation intensity needed to evoke a reliable motor response which is seen as a contraction of the muscle being tested. If muscle contraction is unnoticeable, the amplitude of the MEP recording can be >50 μV. For stimulation, we used a round coil (C-100, 12 cm in diameter). We applied it over the left acromion or at C3-C4 vertebral level at the expected location of the propriospinal neurons of origin, previously confirmed by performing MEP testing (Leszczyńska and Huber, 2023a). The sinusoidal shape stimulus with the duration of 5 ms was used; its strength was at 40-60% of the maximal stimulus output (1.7T) and the frequency at 1 Hz.

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 Shapiro-Wilk test was conducted to assess the normality of distributions. Parameters were compared as dependent groups with a dependent T-Student test (paired difference t-test). P-values of less than 0.05 were considered to be statistically significant. The preliminary statistical analysis was performed to determine the required sample size with the primary outcome variable of RF sEMG amplitude recordings. The test power was established at 80% and a significance level at 0.05 (two-tailed). The mean and standard deviation (SD) were calculated using the data from the first ten subjects. The sample size software estimated that at least 20 subjects were needed for the purposes of this study.

Results

We collected data from MEP recordings following ACR stimulation, when parameters of 52 potentials - 26 per side - from BB and 30 potentials – 16 collected for RF on the right side and 14 on the left side were analysed (Table 1). Values of amplitude collected from stimulation at ACR varied from 100 to 8000 μV in BB and from 100 to 800 μV in RF. Analysing the mean valuse of amplitudes, we calculated a sequence of muscle activation was as follows: first activation was from left BB, second was from right BB; then were activated right RF and lastly left RF (Figure 1 C). Following stimulation at C3-C4, the MEP amplitudes recorded from BB were quite similar with insignificant differences. Recordings from RF had similar results where the left one was compared to the right one, and has lower amplitudes by only 10 μV. Latencies analogously to amplitudes varied significantly in results collected following the ACR stimulation compared to stimulation induced at C3-C4.

Table 1. Data on amplitudes, latency, statistically significant differences and sequence of detected activity based on MEP recordings collected from stimulation at acromion and C3-C4, respectively. $p < 0.05$ determines significant statistical differences marked with bold.

BICEPS BRACHII recordings									
Parameter	Side	Acromion stimulation				C3-C4 stimulation			
		min	max	mean	SD	min	max	mean	SD
Amplitude (μV)	L	400	8000	1665.4	±1717.9	600	12000	1868	±2383.2
	R	100	6000	1330.8	±1252.4	200	8000	1860	±2012.9
p-value	L vs R	NA	NA	**0.04**	NA	NA	NA	1.0	NA
Latency	L	2.7	6	3.9	**±**0.7	2.8	6	4.1	±0.8
	R	3.2	9	4.9	**±**1.3	2.8	6.4	4.3	±0.9
p - value	L vs R	NA	NA	**0.03**	NA	NA	NA	0.07	NA
Frequency	L	26				25			
	R	26				25			
Sequence	L	1				1			

	R	2				2			
RECTUS FEMORIS recordings									
Parameter	Side	Acromion stimulation				C3-C4 stimulation			
		min	max	mean	SD	min	max	mean	SD
Amplitude (μV)	L	100	400	178.6	±97.5	100	1600	596.7	±484.2
	R	100	800	368.8	±11.6	100	1500	586.7	±456.1
p--value	L vs R	NA	NA	**0.02**	NA	NA	NA	1.0	NA
Latency	L	18.5	60	25.6	±11.6	19.9	80	29.1	±15.1
	R	19.9	62	28.3	±11.1	19.5	85	29.7	±16.1
p - value	L vs R	NA	NA	**0.03**	NA	NA	NA	0.921	NA
Frequency	L	14				15			
	R	16				15			
Sequence	L	4				3			
	R	3				4			

Measurements of the efferent conduction velocity of neural impulses which were calculated from latencies and conduction distances after magnetic stimulation at the levels of ACR and C3- C4, respectively, have shown, that they were slower when the cervical point was stimulated (Table 2). The mean velocity of the nerve impulse was 40 m/s from ACR versus 34,83 m/s from C3-C4 to RF. The reason for this surprising phenomenon was caused by the influence of the afferent component, included in the ACR excitation, which, in general, has a larger diameter and consequently faster conduction velocity. The conduction of the sensory component is expected to be about 17.3 m/s. Nevertheless, the range of the conduction velocity detected in our observation is characteristic of the neural transmission detected for propriospinal system fibers.

Table 2. Results on the parameters used for the calculations of conduction velocity. The average values are presented.

Parameters

Stimulation and recording sites	Distance (mm)	Latency (ms)	CV (m/s)
ACR —> RF	1250	25,6	40
C3/C4 —> RF	1010	29	34,83
C3/C4 —> LS	520	15	34,66

Discussion

This study provided the neurophysiological evidence, that different fractions of the fibers in the long cervico-lumbar propriospinal system are activated following the magnetic stimulus applied at ACR via the afferent connections or only at C3-C4 cells of origin. However, they both transmit the neural signals in a velocity range characteristic of the propriospinal system. Moreover, we have presented that stimulation using the single magnetic field stimulus might be successfully used as a source of stimulus in Vojta kinesiotherapy, providing the activation of the propriospinal system. Interneurons in the thoracic spinal cord play an important role not only in controlling respiratory and trunk muscles, but also in providing possible substrates for recovery after spinal cord injury (Saywell *et al.*, 2011). These interneurons conduct the neuronal impulses at an average velocity in the lumbar region of 37.9 m/s compared to 44.5 m/s in the cervical region (Kostyuk *et al.* 1971; Vasilenko *et al.* 1972; Baev *et al.* 1973). According to a study of Mrówczyński *et al.* (2001), the propriospinal neurons produce lateral branches ascending to the inferior cerebellar peduncle and descending to the sacral segments. However, they are predominantly located in the C3-C4 spinal cord and are the ones that contribute to the restoration of respiration after spinal cord injury (Cowley *et al.*, 2021). Propriospinal fibers have been presented to have significant role in rehabilitation. Tohyama *et al.*, (2017) had proved that monkeys with excluded propriospinal component did not fully recover the motor function in 1-3 months after the spinal lesion, even though that they were given longer recovery time, in comparison to monkeys without such a factor. To the same conclusions came many other researchers (Filli and Schwab, 2015; Cowley et al., 2021; Cheng and Guan, 2023). By using the same method that we have described in this article, the effects of MEPs on PNS can be further investigated, as how it affects recovery after the spinal cord injury or stroke, how they behave in patients during rehabilitation, especially in therapies based on spinal cord reflexes such as Vojta therapy or proprioceptive neuromuscular facilitation. This field of research remains very unclear when it refers to humans.

Figure 2 presents the scheme of activation sequences of upper and lower extremities muscles based on recordings of MEP, when the magnetic stimulus was used for the excitation of the afferent component at acromion.

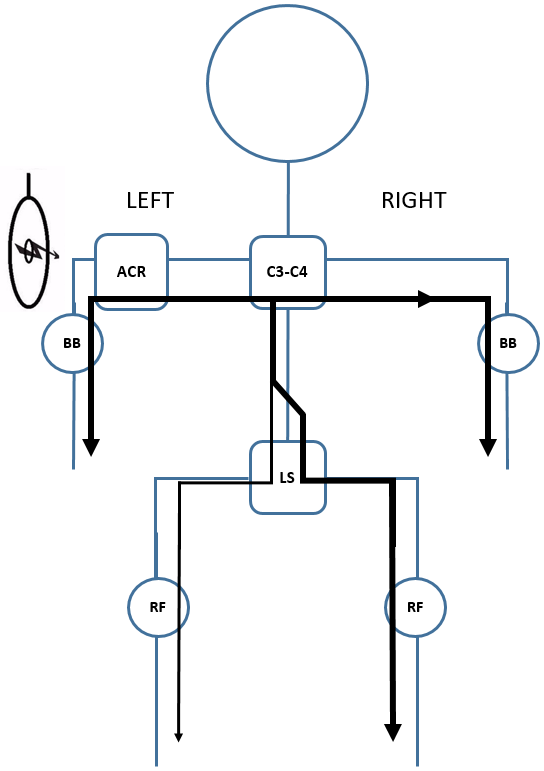

Figure 2. Simplified scheme presenting activation sequences of upper and lower extremities muscles based on recordings of MEP, when the magnetic stimulus was used for the excitation of the afferent component at acromion. Bold lines represent more crossed than uncrossed routes which are considered to mediate the actions predominately. Abbreviations: ACR--acromion, C3-C4 - location at the cervical levels the cells of origin of the long propriospinal fibers, LS - lumbosacral spinal neural centers, BB- biceps brachii muscle, RF - rectus femoris muscle

In our tests, the cumulative values of amplitudes of MEP bilaterally had similar values in muscles, where recordings were performed from when they were induced following C3-C4 stimulation as well and their latency values were similar. This leads to the conclusion that they are transmitted via a similar pathway from the cervical motor centers to the muscles of the right and the left side. Contrary, ACR stimulation on the left side brought the differentiation of amplitude values comparing both sides and latencies longer when MEPs were transmitted with a longer or crossed conduction distance or a **greater number of synapses.** Even so, we think that both nerve pathways might be propriospinal fibers just differing in the number of synapses engaged in the neural transmission.

Those results show that we have probably stimulated two different nerve pathways or at least we have induced impulses on the same pathway but at various length. However, they both transmit the neural signals in a velocity range from 34,6 to 40 m/s which is a characteristic property of the propriospinal system among other efferent spinal pathways. As proved by Skinner et al. (1980), the propriospinal fibers can be stimulated either manually or by electrical pulse which is very similar in effect to the magnetic stimulus that we have used.

One of the biggest problems in neurological patients is the problem of pathologies occurring secondary to damage, especially in the central nervous system (Yokota et al. 2019). We think that our study can help to understand the mechanism of rehabilitation since it brings us closer to understanding which

spinal fiber system may contribute to the compensation of damages in the neural transmission, that follows spinal cord injuries (SCI) or brain injury for example in patients after stroke.

Conclusion

In conclusion, the results of this study prove that potentials transmitted in the spinal cord excited with the magnetic stimulation at acromion, can be considered as a reliable tool for studying the reflex spinal cord pathway including propriospinal system in human, what can make easy to understand the mechanism of action of Vojta or PNF therapies based on the concept by Sherrington and Laslett (1903).

REFERENCES

Baev, K.V., Vasilenko, D.A. and Manzhelo, L.I. (1973) 'Functional properties of propriospinal pathways of the dorsolateral tract of the cat spinal cord', *Neurophysiology*, 5(1), pp. 44–49.

Côté, M.P., Murray, L.M., Knikou, M. (2018) Spinal Control of Locomotion: Individual Neurons, Their Circuits and Functions. Front Physiol. 25;9:784.

Cheng, J. and Guan, N.N. (2023) 'A fresh look at propriospinal interneurons plasticity and intraspinal circuits remodeling after spinal cord injury', *IBRO Neuroscience Reports*, 14, pp. 441–446.

Cowley, K.C. *et al.* (2021) 'Editorial: Propriospinal Neurons: Essential Elements in Locomotion, Autonomic Function and Plasticity After Spinal Cord Injury and Disease', *Frontiers in Cellular Neuroscience*, 15.

De-La-Barrera-Aranda, E. *et al.* (2021) 'Vojta Therapy in Neuromotor Development of Pediatrics Patients with Periventricular Leukomalacia: Case Series', *Medicina*, 57(11), p. 1149.

Filli, L. and Schwab, M.E. (2015) 'Structural and functional reorganization of propriospinal connections promotes functional recovery after spinal cord injury', *Neural Regeneration Research*, 10(4), pp. 509–513.

Gajewska, E. *et al.* (2018) 'An attempt to explain the Vojta therapy mechanism of action using the surface polyelectromyography in healthy subjects: A pilot study', *Journal of Bodywork and Movement Therapies*, 22(2), pp. 287–292.

Guidelines of the International Federation of Clinical Neurophysiology — European Chapter https://www.ifcn.info/endorsed-guidelines.asp (Accessed on 27th September 2023)

Kaczmarek, A.M. *et al.* (2022) 'Relationships between the Clinical Test Results and Neurophysiological Findings in Patients with Thoracic Outlet Syndrome', *Bioengineering*, 9(10), p. 598.

Kostyuk, P.G., Vasilenko, D.A. and Lang, E. (1971) 'Propriospinal pathways in the dorsolateral funiculus and their effects on lumbosacral motoneuronal pools', *Brain Research*, 28(2), pp. 233–249.

Leszczyńska, K. and Huber, J. (2023a) 'The Role of Transcranial Magnetic Stimulation, Peripheral Electrotherapy, and Neurophysiology Tests for Managing Incomplete Spinal Cord Injury', *Biomedicines*, 11(4), p. 1035.

Leszczyńska, K. and Huber, J. (2023b) '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', *Applied Sciences*, 13(13), p. 7609.

Mrówczyński, W., Grottel, K. and Krutki, P. (2001) 'Neurones in the cervical enlargement of the cat spinal cord antidromically activated from sacral segments

and the inferior cerebellar peduncle', *Neuroscience Research*, 41(2), pp. 135–141.
Saywell, S.A. *et al.* (2011) 'Electrophysiological and morphological characterization of propriospinal interneurons in the thoracic spinal cord', *Journal of Neurophysiology*, 105(2), pp. 806–826.
Sherrington, C.S. and Laslett, E.E. (1903) 'Observations on some spinal reflexes and the interconnection of spinal segments', *The Journal of Physiology*, 29(1), pp. 58–96.
Skinner, R.D., Adams, R.J. and Remmel, R.S. (1980) 'Responses of long descending propriospinal neurons to natural and electrical types of stimuli in cat', *Brain Research*, 196(2), pp. 387–403.
Stålberg, E. *et al.* (2019) 'Standards for quantification of EMG and neurography', *Clinical Neurophysiology*, 130(9), pp. 1688–1729.
Tohyama, T. *et al.* (2017) 'Contribution of propriospinal neurons to recovery of hand dexterity after corticospinal tract lesions in monkeys', *Proceedings of the National Academy of Sciences*, 114(3), pp. 604–609.
Vasilenko, D.A., Kostyukov, A.I. and Pilyavskii, A.I. (1972) 'Cortico- and rubrofugal activation of interneurons forming the propriospinal pathways of the dorsolateral funiculus of the cat spinal cord', *Neurophysiology*, 4(5), pp. 377–385.
Vojta, V. (1965) 'Rehabilitation des spastischen infantilen syndroms. Eigene Methodik.' Beitreage zur Orthop. Traumatol. 12, 557.
Vojta, V., Peters, A. (2007) 'The Vojta Principle.' Springer-Verlag, Berlin, Heidelberg.
Wincek, A. *et al.* (2021) 'The Long-Term Effect of Treatment Using the Transcranial Magnetic Stimulation rTMS in Patients after Incomplete Cervical or Thoracic Spinal Cord Injury', *Journal of Clinical Medicine*, 10(13), p. 2975. **Yokota, K. *et al.*** (2019) 'Pathological changes of distal motor neurons after complete spinal cord injury', *Molecular Brain*, 12(1), p. 4.

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