Physiol. Res. 73: 343-349, 2024 *https://doi.org/10.33549/physiolres.935166*

REVIEW

The Decomposition Method of Surface Electromyographic Signals: A Novel Approach for Motor Unit Activity and Recruitment Description

Petr ŠÁDEK[1], **Jakub OTÁHAL**[2,3]

[1]Biomedical Department, Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic, [2]Department of Developmental Epileptology, Institute of Physiology of the Czech Academy of Sciences, Prague, Czech Republic, [3]Department of Pathophysiology, Second Faculty of Medicine, Charles University, Prague, Czech Republic

Received June 20, 2023
Accepted January 9, 2024

Summary

This review aims to describe a novel method in the field of electromyography (EMG), established and improved upon in the last three decades that is able to observe specific parameters of muscle units (MUs). This concept is called the decomposition method, based on its ability to decompose a surface EMG signal to describe muscle activity on the level of individual muscle units in contrast to the level of the whole muscle, as is customary for regular surface electromyography. We provide a brief overview of its history, constituent parts regarding both hardware and software and possible applications. We also acknowledge the state of the research, regarding the background of the decomposition algorithm, the main software component responsible for identifying individual motor units and their parameters. As a result of the ability to describe the behavior of individual motor units during muscle contractions, key concepts in neuromuscular physiology have been put forward, pertaining to the hierarchy of MUs during their recruitment. Together with the recent application for cyclic contractions and gait, the decomposition method is beginning to open up wider possibilities of enquiry.

Key words
Electromyography • EMG decomposition • Motor unit • Gait

Corresponding authors
P. Šádek, Biomedical Department, Faculty of Physical Education and Sport, Charles University, José Martího 269, Praha 6, 162 52, Czech Republic. E-mail: sadekpetr@email.cz and J. Otáhal, Department of Pathophysiology, Second Faculty of Medicine, Charles University, Plzeňská 311, Prague 5, 150 06, Czech Republic. E-mail: jakub.otahal@lfmotol.cuni.cz

Introduction

Over the past two decades, there has been a remarkable advancement in electromyography (EMG), particularly in enhancing the precision and depth of signal description. EMG is a crucial method for monitoring and characterizing the electrical activity within the neuromuscular system, portraying the control signal transmission between the brain and muscles.

In the intricate process of muscle activation, an action potential, originating from the nervous system, reaches the neuromuscular junction and triggers the depolarization of the muscle fiber membrane. This initiates a sequence of neurochemical events culminating in the release of calcium ions from the sarcoplasmic reticulum, thereby triggering muscle contraction [1]. Motor unit action potentials (MUAPs) can be detected by employing an electrode placed either within a muscle extracellular space or on the skin above, capturing an electrical signal that represents the spatial and temporal summation of MUAPs originating from muscle fibers near the sensor.

The distinctive parameters of this signal exhibit variations contingent upon the nature of the contraction, among other factors. Consequently, the analysis of maximal voluntary isometric contraction, the timing of muscle activations, and various other parameters can be

PHYSIOLOGICAL RESEARCH • ISSN 1802-9973 (online) - an open access article under the CC BY license
© 2024 by the authors. Published by the Institute of Physiology of the Czech Academy of Sciences, Prague, Czech Republic
Fax +420 241 062 164, e-mail: physres@fgu.cas.cz, www.biomed.cas.cz/physiolres

derived. This analytical approach finds applications in diverse settings, including establishing reference values for muscle activity, monitoring muscle activity during gait pre- and post-intervention [2], clinical assessment of neurological diseases [3], and a myriad of other practical applications.

The evolution of EMG has seen a few milestones in the past century. The first experiments using an electric current to stimulate muscles date as far back to the 18th century, where Luigi Galvani (1737-1798) showed that electrical stimulation of a frog's leg produced a contraction of the muscles and generated a force. One hundred years later, DuBois-Reymond (1818-1896) was the first to detect a voluntarily elicited electrical signal from human muscles by using a surface electrode (made by a wire attached to a blotting paper immersed in a jar of saline solution) and a galvanometer. From there, the rise of electromyography took a faster pace and saw a clinical use as well, through the work of Guillaueme Duchenne (1806-1875). Even larger impact had the introduction of the first needle electrode, provided through the work of Edgard Adrian (1889-1977) and Detlev Bronk (1897-1975). This innovation laid the foundation to the techniques still used in the research and clinical practice. From there, a series of technological advances were responsible for better hardware and software of EMG, rewarding us with a deeper understanding of muscle function [4].

Electromyography is now regarded as a common procedure to track and observe events in the neuromuscular system, especially regarding the path through which the electrical impulse travels. Providing a very specific information about the state of various parts of the nervous system and its interactions with other related structures, EMG sees its use in clinical practice as well as in the research environment. We are able to diagnose neuromuscular and degenerative diseases, assess movement patterns, and provide reasonings for exercise selection, amongst other things, through the improvements on the field of electromyography.

The current state of EMG

To obtain valuable information about the state of neuromuscular structures, two different variations of EMG are currently used in both clinical and research environments. Surface electromyography uses sensors applied on the skin over a specific part of a muscle, and intramuscular EMG, which uses subdermal sensors inserted directly into the muscle. Both variations have their disadvantages, either the possibility of lower quality of acquired signal in the case of surface EMG (sEMG), or restricted detection volume after an invasive application of the sensors. Thus, a need for a signal of better quality, which can be acquired non-invasively and has a sufficient yield of data led to an algorithm-based method to assess sEMG signals from the surface of the human body.

Apart from the above-mentioned disadvantages, another requirement commonly placed upon EMG signals is the reliability and the level of depth of the acquired signal. Both extraction methods, surface and needle, have similar difficulties with repeated measurements due to a possible movement of the patient, thus lacking the reliability to confidently track the same motor units. Given the use of EMG in clinical settings as a diagnostic or assessment tool, these constraints seem crucial. For example, in a neurodegenerative disease such as amyotrophic lateral sclerosis, electromyographic evaluation is a vital part of the diagnostic process, with the preferred and superior method being the intramuscular EMG. However, as mentioned before, this method has its own disadvantages due to invasive application and the inability to reliably reproduce the positioning of the sensor in repetitive evaluations [3]. To be considered is also the scale of the obtained EMG signal, which refers to muscle activity on the level of the whole muscle, a rather macroscopic scale, albeit partly specific due to the electrode placement. This type of application might suffice for certain diagnostic role [5], although there is a distinct need for more specific, directed insight. The novel approach, developed over the last few decades partly responds to the shortfalls of both EMG variants, offering a much deeper understanding of the communication between the brain and the muscle on the motor unit level.

The decomposition method

Expanding upon the common method of collecting and processing sEMG signals, a novel method is being used to track specific motor units with unprecedented precision. A signal, obtained from sEMG electrodes placed in a specific manner, is decomposed into constituent motor unit action potential trains (MUAPTs), leading to the method referred to as surface EMG decomposition (dEMG). The decomposition is achieved by a specific algorithm using a specially developed knowledge-based Artificial Intelligence framework [6], one of which was first described by the team led by Carlo De Luca at the Neuromuscular Research Center at Boston University [7,8]. However, the prerequisite for the decomposition method is a high-density EMG signal combined with a specific mathematical algorithm capable of tracking and identifying specific motor units in the obtained data. The EMG signal is usually recorded by a number of electrodes in a specific position to each other, providing multiple signals of the same muscle. The decomposition algorithm then tries to identify as many templates of various MUAP as possible, which is done by classifying the shapes and amplitudes of the action potentials tracked by the sEMG sensor [11]. The matching of the MUAP templates against the remaining sEMG signal, the possible superpositions of action potentials and other variables are then resolved to arrive at a number of MUAPTs, which are recognized and tracked through the decomposition algorithm with 90-95 % confidence [11]. Each unique motor unit is then distinguished by a unique signature (Fig. 1). Given the importance of this method, a number of authors have presented algorithms – including Nawab, LeFever, McGill and Adam, to name a few [6,9].

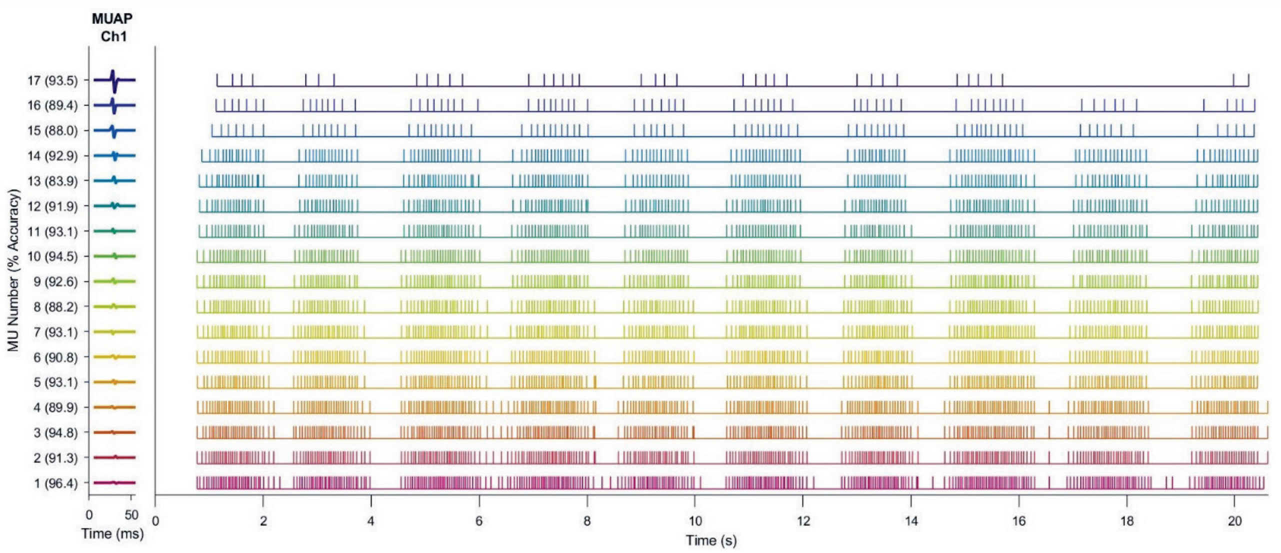

Fig. 1. A graphic representation of MUs firing instances from the vastus medialis muscle during a cyclic squatting task acquired through EMG signal decomposition. The image represents each instance of activation of a given motor unit during the whole task. The columns on the left show a specific EMG signature of each acquired motor unit, their reference number and the accuracy as a percentage which relates to the level of confidence in recognizing a given MU. Graphic was obtained through EMGworks (Delsys Inc., Boston, USA) from author's own work.

The decomposition of sEMG signal saw its first use in describing isometric contractions of a few selected surface muscles including the deltoid, first dorsal interosseous and the tibialis anterior [7,8] with more recent studies looking at the biceps brachii and vastus medialis [10,11]. With the evolution of both the hardware and software, not only was it possible to decompose anisometric contractions, but functional movement such as gait as well. While there were more groups presenting their own versions of decomposition algorithms, all of them required high-yield EMG to be able to provide the required depth and precision of motor units' description. In its core, a decomposition algorithm receives four sEMG signals from close vicinity and through examination and filtering recognizes and then tracks specific signatures of MU action potential trains (i.e. a sequence of pulses). The algorithm identifies signatures of a number of motor units – usually between 5 to 30 [10,12], thus giving us the ability to describe the hierarchy, recruitment pattern, firing rates, amplitudes and other parameters of the tracked motor units (Fig. 1).

The decomposition method brings a unique opportunity to submit data regarding individual motor units to statistical analysis. While there are observed parameters of each motor unit, such as their signature, recruitment and derecruitment threshold, amplitude and more, which alone provide a useful insight into mechanisms of muscle contraction, its the sum of the collected data for a group of motor units which provides a possibility to infer changes in neuromuscular coordination during different tasks. Through analysis we can then correlate changes of specific parameters, such as recruitment order or firing rate during different tasks to then obtain a deeper look into the change of neuromuscular mechanisms. One example can be provided by using the decomposition method on data collected by EMG from vastus lateralis in older population to observe a decrease of maximal firing rate, possibly due to neurodegeneration [13]. This is then paired with an absolute increase of number of motor units recruited for given tasks to make up for the overall lower firing rate, thus yielding the desired level of force production. This is just one of many possible situations where the deeper level of observation, provided by the decomposition method, provided additional information needed.

Technological and practical background

The depth and quality of information obtained through dEMG depend on both the hardware (electrodes and the acquisition system) and the software (the decomposition algorithm). The hardware consists of a 4 or 5-blunt ended pin surface sensor array which receives EMG signals from a 4-bipolar electrode or single differential arrangement to enable high signal quality. This helps to reduce background noise (from different extrinsic sources) and allows the identification of MUAPTs even when there is a superposition of different MUs, when 2 or more motor units are firing at the same time. The second part of the hardware is the sEMG system, providing acquisition and filtering, which then transfers the data from the sensor (with the data being analog at the time) to a computer (arriving in digital format). The digital data is then decomposed through the dEMG software and information about individual motor units can be described including the number of motor units gathered, the quality of the data itself, MUs firing rates, the recruitment thresholds, the amplitude and shape of the motor units and various other characteristics [10,12].

To ensure the quality of the sEMG data, a number of precautions should be taken. For example, choosing the correct location where to place the electrode is crucial in order to gather as many motor units as possible. A detailed map of preferred locations for individual muscles can be found in Zaheer and colleagues [14]. Other steps include skin preparation and proper sensor anchorage, ensuring minimal sensor movement on the skin. This step is particularly important in dynamic contraction, where the dEMG method encounters a specific challenge – the muscle and superficial layers (i.e. skin) move during movement, changing relative position to one another. This can be expressed as an intercycle or intracycle MUAP signal change, which can be described as the specific signal, its pattern and time variables, leading to changes in a given MU during one contraction cycle or between contraction cycles. To counter this, a machine-learning algorithm was used to decompose a great number of increasingly difficult MUAP patterns, mimicking dynamic contractions [10]. This then led to the higher precision of the decomposition algorithm and higher MUAP yield, thus making it possible to track multicycle dynamic tasks, such as repeated biceps flexion or gait [10]. It was the first study to report a high-yield decomposition of dynamic contraction, tracking 20 motor units at 92 % accuracy (meaning 20 different motor units and their action potential trains were recognized with 92 % confidence). The high accuracy represents our ability to confidently track the same motor units in successive muscle activations, which can prove crucial in clinical settings. For example, specific diagnostic tests for amyotrophic lateral sclerosis rely on observing change of parameters of the same motor units in successive trials, thus requiring test re-test reliability to give greater confidence in the reported behavior [3].

Neurophysiological applications

The relevance of dEMG method is clearly substantiated by the information obtained through its use and has implications for advances in the field of neurophysiology. Through EMG decomposition, the concept of common drive was established by De Luca and colleagues, referencing a specific motor unit recruitment strategy [7,11]. This term describes a net excitation of a given motor unit pool which is responsible for the force level produced and the MUs behavior. It was hypothesized that instead of a collective, yet solitary activation of MUs within a given muscle, which would produce the force required, a common drive governs a selection of motor units, which are then recruited accordingly to the task. This would then put less demand on the CNS as it would not need to control each individual motor unit separately [15]. The onion skin scheme, which describes the order of activation of motor units during tasks in regards to their hierarchy, was also obtained through rigorous analysis of EMG data, providing us with valuable insight into the relationship between specific parameters of given motor units, the order of their activation and firing rates [7,16,17].

The onion skin model, as the second breakthrough derived from dEMG data, puts forth a relationship between firing rate and recruitment time, where earlier recruited motor units maintain faster firing rates than those recruited later. This notion expands upon the Henneman‘s Size principle, which states that with increased excitation to the motor pool (meaning an increase of force produced), motor units are recruited in order of increasing size. However, the uncertainty lied in the specific parameters and relationship between the firing rate, time of recruitment and the size of motor units during muscle contractions. Through stimulation of anesthetized cats, it was first promulgated that the larger motor units have greater firing rates, while the smaller motor units require lower firing rates in order to tetanize (produce twitch fusion, responsible for larger muscle contractions). In direct contrast to this notion, through experiments on voluntary contractions in humans, the opposite was observed, where the earlier-recruited motor units (and also the smaller ones) maintain higher firing rates than the later-recruited ones, providing an inverse relationship between firing rate, size and recruitment threshold [4]. If plotted graphically, the firing rate – recruitment time relationship forms layers, thus reminiscing the layers of an onion. This concept has a number of advantages, providing us with a more economic muscle contractions, which benefits low effort activities, such as those in our daily lives. The onion skin scheme also provides a smoother contractions, again providing benefits for daily activities such as hand manipulation. While first noted during isometric contractions, later work by De Luca on cyclic contractions suggests the same rule might also apply to this situation (Fig. 2) [10].

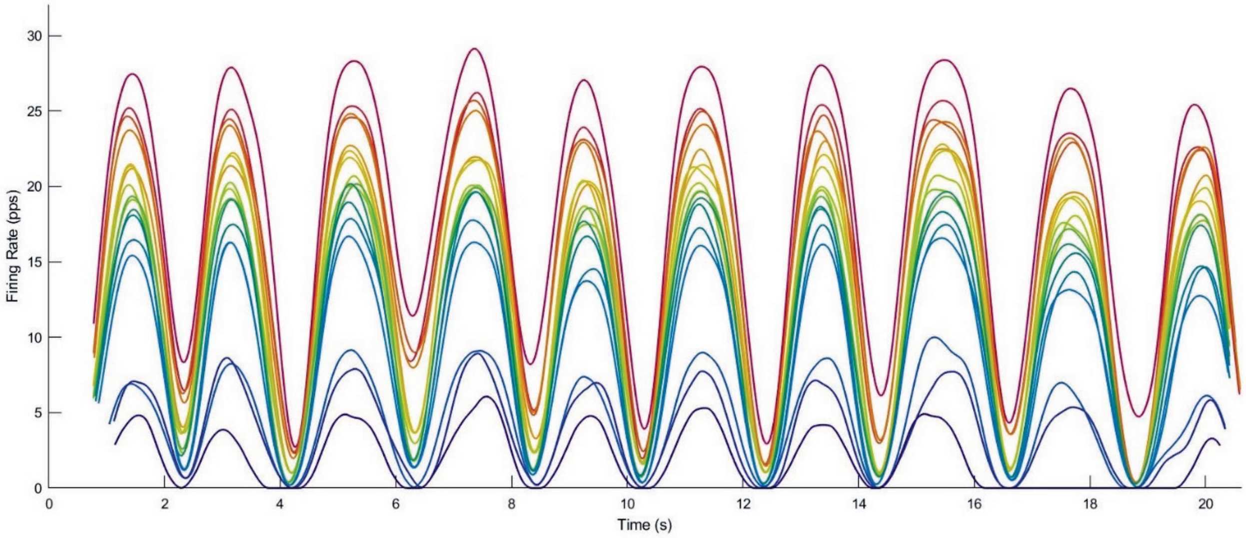

Fig. 2. A graphic representation of MUs firing rates during a cyclic squatting task acquired with EMG signal decomposition. Each motor unit is depicted by a specific color as per the previous figure. Graphic was obtained through EMGworks (Delsys Inc., Boston, USA) from author‘s own work.

Possible applications of the decomposition method

While the use of EMG data analysis and decomposition for neurophysiological research is undeniably paramount, applications in clinical research must be acknowledged as well. As mentioned before, the decomposition method offers a very reliable source of data without the negative effects of the intramuscular EMG, making it more attractive to use when working in a clinical environment. The work done by Lindley [11] on patellofemoral pain using dEMG to describe the relationship between the vastus medialis and vastus lateralis and the possible changes in neuromuscular control of these muscles represents this advance. Part of the study was an intervention as well, looking into the effect of taping on biomechanical and neurophysiological properties [11]. This is one of the first applications of dEMG methods in a clinical population, shedding light on the etiopathology of this syndrome and hopefully providing an example of what this advanced electromyographic method is capable of.

Other possible areas, which might benefit from the decomposition method, are related to neurodegenerative diseases. EMG is often viewed in this instance as the golden standard for the diagnostic purposes or in order to track the treatment effect in patients suffering from neurological diseases (such as progressive muscular dystrophy, amyotrofic lateral sclerosis, myastenia gravis and many more). Since these disorders affect mainly the neuromuscular system and its interactions, which can be observed as abnormal motor behavior, the loss of strength or muscle control, there is an imperative for clinicians to be able to reliably assess the integrity of neuromuscular components responsible for the mentioned aberrations. The usual practice relies on needle EMG for its reliability and precision, however, the forementioned difficulties related to its application and patient‘s comfort provide an opening for a method, which could provide sufficient, or even better quality of information while putting less stress on the patient. In instances, where the disease results in changes of motor unit parameters, such as different amplitude, recruitment threshold or firing rate (examples could be chronic denervation or other types of nerve damage or healing, ALS and others), the decomposition method can provide valuable diagnostic insight [18].

In more functional approach, strength training or exercise in itself is a broad topic benefiting enormously from the ability of EMG and decomposition method to observe preferential muscle activation during a specific position or to describe a reaction of the neuromuscular system after a bout of training. We are able to observe changes in amplitude and conduction velocity, differences in firing rate of tracked motor units or force fluctuations during prolonged contractions, all being related to reactions of the neuromuscular system to the demands during a physical activity [19].

Conclusions

The dEMG is a novel method, put forward by De Luca, Nawab, Richards, and other authors, which provides a much deeper insight into the motor unit function and coordination during different tasks. With the current advances, it is now possible to track multiple motor units during dynamic, cyclic tasks such as squats, lunges, or gait. The dEMG technique, characterized by its capacity to deliver distinct information, exhibits utility in both clinical and research settings. Expanding upon the concepts of common drive and the onion skin model, the utilization of the decomposition method allows for the monitoring of motor unit activation and coordination across various exercises. This may facilitate the characterization of preferred muscle activation patterns and precise temporal sequencing during movement execution. In the context of clinical applications, the incorporation of dEMG holds promise, as emerging evidence suggests the presence of disrupted neuronal drive in prevalent musculoskeletal conditions like patellofemoral pain. This implies that an underlying pathological factor could potentially lie within the realm of muscle activation [11]. Taking a step forward, the real-time observation of motor units in the vastus medialis during squats using wireless dEMG represents a tangible tool that could soon find its place in clinical practice.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

The authors would like to express their gratitude for the help provided by the University of Central Lancashire, namely to Jim Richards, Ambreen Chohan and Graham Chapman.

References

1. Shishmarev D. Excitation-contraction coupling in skeletal muscle: recent progress and unanswered questions. Biophys Rev 2020;12:143-153. https://doi.org/10.1007/s12551-020-00610-x
2. Žarković D, Šorfová M, Tufano JJ, Kutílek P, Vítečková S, Ravnik D, Groleger-Sršen K, Cikajlo I, Otáhal J. Gait changes following robot-assisted gait training in children with cerebral palsy. Physiol Res 2021;70(Suppl 3):S397-S408. https://doi.org/10.33549/physiolres.934840
3. Bashford J, Mills K, Shaw C. The evolving role of surface electromyography in amyotrophic lateral sclerosis: A systematic review. Clin Neurophysiol 2020;131:942-950. https://doi.org/10.1016/j.clinph.2019.12.007
4. De Luca CJ, Contessa P. Biomechanical benefits of the Onion-Skin motor unit control scheme. J Biomech 2015;48:195-203. https://doi.org/10.1016/j.jbiomech.2014.12.003

5. Jombík P, Spodniak P, Bahýľ V, Necpál J. Visualisation of Parkinsonian, essential and physiological tremor planes in 3Dspace. Physiol Res 2020;69:331-337. https://doi.org/10.33549/physiolres.934066
6. De Luca CJ, Adam A, Wotiz R, Gilmore LD, Nawab SH. Decomposition of surface EMG signals. J Neurophysiol 2006;96:1646-1657. https://doi.org/10.1152/jn.00009.2006
7. De Luca CJ, LeFever RS, McCue MP, Xenakis AP. Control scheme governing concurrently active human motor units during voluntary contractions. J Physiol 1982;329:129-142. https://doi.org/10.1113/jphysiol.1982.sp014294
8. Mambrito B, De Luca CJ. A technique for the detection, decomposition and analysis of the EMG signal. Electroencephal Clin Neurophysiol 1984;58:175-188. https://doi.org/10.1016/0013-4694(84)90031-2
9. Enoka RM. Physiological validation of the decomposition of surface EMG signals. J Electromyogr Kinesiol 2019;46:70-83. https://doi.org/10.1016/j.jelekin.2019.03.010
10. De Luca CJ, Chang SS, Roy SH, Kline JC, Nawab SH. Decomposition of surface EMG signals from cyclic dynamic contractions. J Neurophysiol 2015;113:1941-1951. https://doi.org/10.1152/jn.00555.2014
11. Lindley S. *The Neuromuscular and Mechanical Control of the Knee Joint in Patellofemoral Pain Sufferers*. Preston, 2015. Dissertation. University of Central Lancashire.
12. De Luca CJ, Hostage EC. Relationship between firing rate and recruitment threshold of motoneurons in voluntary isometric contractions. J Neurophysiol 2010;104:1034-1046. https://doi.org/10.1152/jn.01018.2009
13. Girts RM, Mota JA, Harmon KK, MacLennan RJ, Stock MS. Vastus Lateralis Motor Unit Recruitment Thresholds Are Compressed towards Lower Forces in Older Men. J Frailty Aging 2020;9:191-196.
14. Zaheer F, Roy SH, De Luca CJ. Preffered sensor sites for surface EMG signal decomposition. Physiol Meas 2012;33:195-206. https://doi.org/10.1088/0967-3334/33/2/195
15. De Luca CJ, Erim Z. Common drive of motor units in regulation of muscle force. Trends Neurosci 1994;17:299-305. https://doi.org/10.1016/0166-2236(94)90064-7
16. De Luca CJ, Contessa P. Hierarchical control of motor units in voluntary contractions. J Neurophysiol 2012;107:178-195. https://doi.org/10.1152/jn.00961.2010
17. Nawab SH, Chang SS, De Luca CJ. High-yield decomposition of surface EMG signals. Clin Neurophysiol 2010;10:1602-1615. https://doi.org/10.1016/j.clinph.2009.11.092
18. Mills KR. The basics of electromyography. J Neurol Neurosurg Psychiatry 2005;76(Suppl 2):ii32-ii35. https://doi.org/10.1136/jnnp.2005.069211
19. Stožer A, Vodopivc P, Križančić Bombek L. Pathophysiology of exercise-induced muscle damage and its structural, functional, metabolic, and clinical consequences. Physiol Res 2020;69:565-598. https://doi.org/10.33549/physiolres.934371