Assessment of Muscles Fatigue Based on Surface EMG Signals Using Machine Learning and Statistical Approaches: A Review

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Abstract. Muscle fatigue is described by the decline in muscle maximum force during contraction. The fatigue occurs in the nervous or muscle fibre cells. The nerves produce a high-frequency signal to gain the maximum contraction, but it cannot sustain the high frequency signal for a long time, and that leads to a decline in muscle force. The surface Electromyography (EMG) is the dominant method to detect muscle fatigue because the EMG signals give more information about the muscle’s activities. This review discussed the EMG signal processing and the methods of detection muscles fatigue with three domains (time domain, frequency domain, and time-frequency domain) based on EMG signals that are collected from the muscles during dynamic and static movements.

Keywords: muscles fatigue, EMG, dynamic and static movement

1. Introduction
Muscle fatigue is described by the decline in muscle maximum force during contraction [1]. Acute fatigue affects our ability to lift or move. Many types of research have carried out a further study to detect and study muscle fatigue. Currently, there are many detection methods that are applied to muscle signals in order to detect fatigue [2]. However, the surface electromyography (sEMG) is the main method to record and study the muscles functions, by recording the electrical signal of the muscles. There are also many factors that can contribute to fatigue [3], like muscle fiber composition, regulation of Ionic in the bloodstream, energy supply, neural factors, and many other factors. The studies have indicated that muscle fatigue is related to the incidence of musculoskeletal injuries occurring in sports training and competition [4]. Nyland [5] made the comment that fatigue during running might be related to lower extremity injury. Recently, evidence has shown that muscle activation patterns and kinematics are altered due to fatigue. Hence, it may raise the possibility of the occurrence of an injury to both the muscles as well as the bones injury [6]. Pinniger [7] found that after a specific hamstring fatigue exercise, the kinematic data of sprinting were changed. The kinematics could display alteration owing to the functional changes which occur in order to prevent or minimize the level of unpleasantness and the occurrence of fatigue [8]. Rodacki [9] echoed that the regulation of movement of the individual portions is controlled and ultimately decided by the force of muscle, which when sufficient fatigue has occurred may display certain changes. They also concluded that this phenomenon gave a clue as to the available of a supporting methodology to negate the losses occurred during the process of the force-development characteristics which occurs
within the muscles owing to fatigue. In this paper, we will discuss the muscles fatigue during dynamic and static movements, EMG signal processing, methods of detection muscles fatigue.

2. Muscles Fatigue Measurements
The disparity in the opinion of the mechanism of muscle fatigue can be partially elaborated with the use of various models of exercise, procedures, and processes done applied to quantify fatiguing of muscles. With an objective, a quantifiable and continuous method to assess muscle fatigue, this will amplify the knowledge of ergonomics, work, and injury resulting from work physiology [4]. The single most relevant determination of fatigue is done through the measurement of force or power measurement, which is produced during the course of a voluntary effort of maximum intensity, maximal voluntary contractions (MVCs) test. In general, when the subject performs the task of interest or the fatigue task continuously, at the pre-, post- and/or the interim time point, brief MVC tests will be conducted to register the drop of maximal force output from particular muscle. This will quantify the muscle fatigue pattern in relation to the task performed. The force output decline rate measured in these MVCs tests will indicate the muscle fatigue pattern. The foundation of similar tests which assists in the direct evaluation includes force measurement equipment. Although the drop of maximal voluntary contractions output directly indicates the presence of muscle fatigue. However, the surface electrodes have the ability to record up the superficial muscle layer’s electrical transmissions, after which it magnified and ultimately the determination of the signal power spectrum is done when the response produced in sEMG.

3. Signal Processing
Electromyogram signals are gradually becoming more essential in various fields of application, such as in prosthesis devices, human to machine interactions, clinical/biomedical, and rehabilitation devices [10]. But, distorted EMG signals possess a major challenge in further expanding the performance applications mentioned above [11]. The EMG signals that are collected from the muscles by the electrodes will have noise, where the noise has a role in the hampering of the recording signals. For this reason, the EMG signal must be filtered in a proper manner to remove any noise [12]. The frequency of noise contaminating the EMG signal may be low or high. Low-frequency noises usually come from an amplifier's direct current offsets. Normally this noise can be avoided with the use of a high pass filter, while the high-frequency noises arise from nerve conduction. The interference of high frequency comes from computers, radio broadcasts and can be removed by using a low pass filter. The high pass filter is used to eliminate the low ranged frequencies that result at the electrical signal collection. The frequencies that are passed with a filter transmission as a band are known as a passband. The frequencies that cannot be passed with a filter are known as stop band [12]. The concept of a low pass filter is opposite to that of high pass filters. This means the frequencies exceeding the cut off value are removed and those below it will be transmitted. The EMG transmission needs to remove the high frequencies and low frequencies, while a specific band of frequencies must be transmitted forward, this is done by using a specific filter called a bandpass filter. This bandpass filter permits for specific bands to be transmitted according to the range that is determined by the user, however, the bandpass filter is very suitable for EMG signals to take a specific range of frequencies that is perfect for the type of analyzing [13]. Figure 1 shows the general procedures of EMG signal processing.

![Figure1. EMG signal processing procedures included filtering, rectifying, and smoothing [14].](image-url)
4. Feature Extraction

Feature extraction is a method to extract useful information from EMG signals during fatigue condition is simply explained as the diminishing of the capacity to generate force within the neuromuscular system. Generally, muscle fatigue is recognized by the EMG signal as long as there is a mutual decline in parameter examined in the frequency domain and time-frequency domain, and an increment in the parameter evaluated in the time domain [15], as shown in Figure 2. The type of EMG features can be divided into three domains: time domain, frequency domain, and time-frequency domain.

![Figure 2. The increment in the pattern of RMS and decline in the pattern of MDF features for the EMG signal during muscle fatigue [24].](image)

4.1. Time Domain Features

The signal recorded in the time domain is filtered to eliminate and minimize the noise, crosstalk, and line noise. The fatigue is related to the increment of the EMG amplitude [16]. The muscle fatigue detection in the time domain can be estimated by extracting features like root mean square (RMS) and mean absolute value (MAV). The detection of fatigue by observing the amplitude of the EMG signal is rarely used, and it will be more accurate if it is combined with other methods such as spectral analysis [17] to get better detection and more reliability. Later was discovered that the connection occurring between signal amplitude and force generated within the muscle are different among fatigue protocol [18]. However, there is a method that use multiple time windows (MTW) to get over this issue, by using different functions like Multiple hamming windows (MHW), multiple Slepian windows (MSW) and Multiple trapezoidal windows (MTRW) [19]. Thus, the signal processing to be combined with another feature extraction for better detection.

4.2. Frequency Domain Features

The shift towards lower frequencies of the EMG frequency spectrum calculated by fast Fourier transform (FFT) method [20]. Where the most common procedure is to monitor the relative changes in the mean (MNF) and median power frequencies (MDF) and to relate these measures to the initial value or non-fatigue state mean and median power frequencies. Kaljumae [21] used the phenomena of the shift of sEMG MNF and MDF towards lower frequencies under the isometric condition to document the change of fatigability of vastus lateralis (VL) and vastus medialis (VM) after 10 weeks of bicycle-ergometer training program in male subjects. Gerdle and Fugl-Meyer [22] had 10 healthy women perform repetitive maximal isokinetic plantar flexion. The sEMG MNF measured on the soleus, gastrocnemius medialis (GM) muscle along with the gastrocnemius lateralis (GL) were decreased in parallel with the work output within the first 50 contractions which was later superseded by constant levels in the resultant 50 contractions. So [23] examined the surface sEMG of rectus femoris(RF) and biceps brachii (BB) collected from 18 athletes when they performed maximal extension of the knee and flexion of the elbow exercises. The calculated MPF by FFT was found to reduce along with the reduction of work output and they suggested that an approximate reduction of 37.2% in relative MPF might be handy in performing the role of a parameter for assessing the level of muscle fatigue.

However, the MDF and MNF are very important to detect the muscles fatigue based on the power spectrum, but it will be more reliability and clarity if it combined with the time domain features to get more information about the function of the muscles.
4.3. Time Frequency Domain Features
Muscle fatigue is related to both EMG signal characteristics each in a different way, that leads to
the Joint analysis of EMG spectrum and amplitude (JASA). This analysis has 4 situations to determine
force and fatigue, first when both amplitude and spectrum increases that’s mean force increase, second
when both amplitude and spectrum decreases that’s mean force decrease, third when amplitude
increase and spectrum decrease that’s mean fatigue, fourth when amplitude decrease and spectrum
increased that’s mean recovery [4]. Time-frequency methodologies are utilized to extensively
study signals in which there is considerable variation of the frequency content with the change in time,
which is similar to the situation seen in muscle fatigue. Short-Time Fourier Spectrum (STFT) is
considered as a relatively common time-frequency distribution. However, the time-frequency
functions can be utilized in the analysis of sEMG signals arising during a localized fatiguing of
a muscle. Research conducted by Davies and Reismann clearly states that the STFT has the ability
most accurately depict spectrum compression which occurs during the time of muscle fatigue. In a
study conducted on the relationship which exists between STFT and continuous wavelet transforms
(CWT) to analyze EMG signals from the back and hip muscles during fatiguing
isometric contractions, it was discovered that both methods ultimately give out the same output on
EMG spectral variables [2]. The discrete wavelet transform (DWT) has been used to indicate the low-
level muscles fatigue of brachioradialis (BRD), biceps brachii long head (BBL), and biceps brachii
short head (BBS) when the subjects performing force exertion [25]. The muscle fatigue is seen in
children suffering from cerebral palsy [26]. The muscle fatigue that occurs to PC gamers after
continuous playing [27], and in helicopter pilots who are suffering from lower back pain [28].
Multiple classical, as well as newly designed modern methods of signal processing modalities, are
used [17] these include RMS, zero-crossing rate (ZCR), averaged instantaneous frequency, wavelet
analysis, fractal analysis, and both MNF and MDF. The instantaneous mean and median frequency
(IMNF and IMDF) are added so as to complete the need [29] through the utilization of time-frequency
or time-scale approaches, such as STFT [17], Wigner distribution (WD), Choi-Williams distribution
(CWD) [30], time-varying autoregressive approach (TVAR) [31], and CWT [32].

5. Methods of Detection Muscles Fatigue
There are many non-invasive methods to detect muscle fatigue, the main methods are surface
Electromyography (sEMG) and Mechanomyography (MMG). The EMG records the electrical activity
signal from the muscle, while the MMG record the mechanical activity of the muscle [33]. There are
many other methods but less use in clinical or research in fatigue like sonomyography (SMG) that use
ultrasounds to detect fatigue and controlling prosthesis [34], near-infrared spectroscopy (NIRS) that
use near-IR light to measure the hemoglobin absorption properties, and Acoustic myograph (AMG)
that record the sound of muscles it’s particular application of MMG. Each method tries to record and
analyze one or multi symptoms, signals, and characteristics of muscle. However, the better method for
detection muscles fatigue is surface EMG. There are many researchers collected the EMG signals
from subject’s muscle like BF, Medial Hamstrings (MH), GM, RF, Tibialis Anterior (TA), GL,
Medial Gastrocnemius (GMS), semimembranosus (SEMS), VM, GA, BB, Triceps Brachii (TB), and
VL) to use it as indicator for muscles fatigue index based on using the machine learning (regression)
or statistical approach (ANOVA test), and some of them based on the pattern of the features to
indicate the muscles fatigue as shown in Table 1.
Table 1. Literature review of the methods for detection muscles fatigue during contraction based on EMG signals.

| References | Muscles          | Contraction Protocol                          | Analysis Methods         |
|------------|------------------|-----------------------------------------------|--------------------------|
| Marco [36] | RF, BF, GM       | Cycling 30 minutes constant                   | IMNF                     |
| Christin [37] | GM, BF, VL, RF, TA, GA | Incremental running test on a treadmill | iEMG                     |
| Kumar [38] | RF, GL, GM, VL, VM | Cycling for prolonged constant                | RMS, MF                  |
| Bing Yu [39] | SEMBS, BF       | Running over ground with maximal speed.       | EMG Peak, ANOVA          |
| Takayuki [40] | BB, TB          | Utilized the dumbbell as a burden             | FFT, MPF                 |
| Kenichi [41] | Long Head BB    | Exercise for 8 minutes during low-level isometric contraction. | recurrence quantification analysis |
| Andrezej [42] | RF, BF          | Run 400m on tartan athletic track with a different intensity. | MPF, Linear Regression |
| Ahamed [43] | Middle BB       | Eccentric and concentric contractions         | RMS                      |
| Tatsushi [44] | RF, TA, BF, GM  | Cycling with 70 RPM, 100 watts                | RAW EMG and statistical DWT |
| Rubana [45] | Right RF        | During walking                                | FFT & Spectral Density   |
| Kiran [46]  | TB               | Dumb-bell curl exercise.                      | RMS, Linear Regression   |
| Crozara [47] | RF, VL, BF, GL  | Incremental running on a treadmill           |                          |
| Maner [48]  | RF, VL, VM      | 5km running on variables surface             |                          |
| Ridzuan [49] | GA              | Running on a treadmill for 30min              |                          |
| Mastaler [50] | RF, BF, TA, GAS | Running, 200m/outdoor and 400m/treadmill.    |                          |

6. Discussion
The sEMG is the most dominant method used for muscle function and fatigue detection, where there are many papers describing the fatigue and detecting it. However, the most used analyzing methods are RMS, MNF, MPF, WL, MDF, iMAV, iRMS, IMNF, and IMDF and then applied the statistical analysis or machine learning (ANOVA, Regression Line) based on the linear regression slope values where these values describe the muscles fatigue index as shown in Figure 3. In the time domain the fatigue is related to increment of the EMG amplitude [16], in the frequency domain the shift towards lower frequencies, and in time-frequency domain when the amplitude increase and spectrum decrease that’s mean fatigue [4]. Indeed, the better methods that used for detection muscles fatigue are MDF and MNF were based on the power spectrum analysis of the EMG signals that result from the FFT, because the spectral analysis of the data be more reliable and give more information about the muscles functions compared with the other methods. But it will be more reliability and clarity if it combined with the time domain features to get more information about the function of the muscles and to avoid losing the information. However, the most researches detect fatigue in GM, RF, BF, GMS, GL, VL, and VM muscles because they are easy to implement the electrodes on it and they are superficial muscles, also can control it efficiently. The sEMG can detect fatigue during dynamic and static contraction.
Figure 3. Muscle fatigue detection based on frequency decline with applying linear regression [35].

7. Conclusion
Muscle force production involves a sequence of events, extending from cortical excitation to motor unit activation to excitation–contraction coupling, and ultimately leading to muscle activation. Changes at any level in this pathway, including changes in the nervous, ion, vascular, and energy systems, impair force generation and contribute to the development of muscle fatigue. However, the current states for fatigue detection are still in the research area, therefore must be real application are found for fatigue. Even though the sEMG electrodes and MMG transducers are not meant to be for long time monitoring. Also, very little real time myography fatigue detection is done, there should be some trials in fatigue detection and classification using Neural Network for fast accurate fatigue detection. We believe that the combination of two methods (features) will provide more useful information, compared with the information obtained from uni-method. Therefore, the combination of multi features should be considered to develop and improve the performance of the methods that related with the muscles fatigue assessment.

References
1. González-Izal M, Malanda A, Navarro-Amézqueta I, Gorostiaga EM, Mallor F, Ibañez J, et al. EMG spectral indices and muscle power fatigue during dynamic contractions. J Electromyogr Kinesiol [Internet]. 2010;20(2):233–40.
2. Al-Mulla MR, Sepulveda F, Colley M. A review of non-invasive techniques to detect and predict localised muscle fatigue. Sensors. 2011;11(4):3545–94.
3. Bogdanis GC. Effects of physical activity and inactivity on muscle fatigue. Front Physiol. 2012;3 MAY(May):1–16.
4. Jonkers I, Nuyens G, Seghers J, Nuttin M, Spaepen A. Muscular effort in multiple sclerosis patients during powered wheelchair manoeuvres. Clin Biomech [Internet]. 2004;19(9):929–38.
5. Nyland A, Shapiro R, Stine RI, Horn TS, Ireland ML. Relationship of Fatigued Run and Rapid Stop to
Ground Reaction Forces, Lower Extremity Kinematics, and Muscle Activation. J Orthop Sport Phys Ther. 1994;20(3).
6. Brereton LC, McGill SM. Effects of physical fatigue and cognitive challenges on the potential for low back injury. Hum Mov Sci. 1999;18(6):839–57.
7. Pinniger GJON, Steele JR, Groeller H. Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? Med Sci Sport Exerc [Internet]. 2000;32(3):647–53.
8. Van Dieën, J. H., Toussaint, H. M., Maurice, C., & Mientjes M. Fatigue-related changes in the coordination of lifting and their effect on low back load. J Mot Behav. 2005;28(4):304–314.
9. Rodacki ALF, Fowler NE, Bennett SJ, Bota J. Multi-segment coordination: fatigue effects. Med Sci Sport Exerc. 2001;33(5):1157–67.
10. Chowdhury RH, Reaz MBI, Alauddin M, Mohd B, Bakar AAA, Chellappan K, et al. Surface Electromyography Signal Processing and Classification Techniques. Sensors. 2013;12431–66.
11. Reaz MBI, Hussain MS. Techniques of EMG signal analysis: detection, processing, classification and applications (Correction). Biol Proced Online. 2006;8(April 2005):2006.
12. Kumar JS, Kannan. Human Hand Prosthesis Based On Surface EMG Signals for Lower Arm Amputees. Int J Emerg Technol Adv Eng. 2013;3(4).
13. De Luca CJ, Donald Gilmore L, Kuznetsov M, Roy SH. Filtering the surface EMG signal: Movement artifact and baseline noise contamination. J Biomech [Internet]. 2010;43(8):1573–9.
14. By Leandro Ricardo Altimari, José Luiz Dantas, Marcelo Bigliassi, Thiago Ferreira Dias Kanthack AC de M and TA. Influence of Different Strategies of Treatment Muscle Contraction and Relaxation Phases on EMG Signal Processing and Analysis During Cyclic Exercise. Comput Intell Electromyogr Anal Perspect Curr Appl Futur Challenges IntechOpen. 2012;
15. Roman-liu D, Tokarski T, Wo K. Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load. 2004;14:671–82.
16. Kallenberg, L. A., Schulte, E., Disselhorst-Klug, C., & Hermens HJ. Myoelectric manifestations of fatigue at low contraction levels in subjects with and without chronic pain. J Electromyogr Kinesiol. 2007;17(3):264–274.
17. Cifrek M, Medved V, Tonković S, Ostojić S. Surface EMG based muscle fatigue evaluation in biomechanics. Clin Biomech. 2009;24(4):327–40.
18. Dideriksen, J. L., Farina, D., Baekgaard, M., & Enoka RM. An integrative model of motor unit activity during sustained submaximal contractions. Am J Physiol Circ Physiol. 2010;
19. Venugopal G, Navaneethakrishna M, Ramakrishnan S. Extraction and analysis of multiple time window features associated with muscle fatigue conditions using sEMG signals. Expert Syst Appl [Internet]. 2014;41(6):2652–9.
20. Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams C. Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. Ergonomics. 2000;25(3):213–223.
21. Kaljumäe, U., Hänninen, O., & Airaksinen O. Knee extensor fatigability and strength after bicycle ergometer training. relives Phys Med Rehabil. 2003;75(5):564–7.
22. Gerdl, B., & Fugl Meyer AR. Is the mean power frequency shift of the EMG a selective indicator of fatigue of the fast twitch motor units? Acta Physiol Scand. 1992;145(2):129–38.
23. So, R., Chan, K. M., & Siu O. EMG power frequency spectrum shifts during repeated isokinetic knee and arm movements. Res Q Exerc Sport. 2002;73(1):98–106.
24. Guo W, Sheng X, Zhu X. Assessment of muscle fatigue by simultaneous sEMG and NIRS: From the perspective of electrophysiology and hemodynamics. In: International IEEE/EMBS Conference on Neural Engineering, NER. 2017. p. 33–6.
25. Zhang G, Morin E, Zhang Y, Etemad SA. Non-invasive detection of low-level muscle fatigue using surface EMG with wavelet decomposition. In: Conference proceedings: . Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Annual Conference. 2018. p. 5648–51.
26. Leunkeu, A. N., Keefer, D. J., Imed, M., & Alhamed S (2010). Electromyographic (EMG) analysis of quadriecps muscle fatigue in children with cerebral palsy during a sustained isometric contraction. J Child Neurol. 2010;25(3):287–93.
27. Oskoei MA, Member S, Hu H, Member S. Support Vector Machine-Based Classification Scheme for Myoelectric Control Applied to Upper Limb. 2008;55(8):1956–65.
28. Balasubramanian, V., Dutt, A., & Rai S. Analysis of muscle fatigue in helicopter pilots. Appl Ergon.
2011;42 (6):913–918.
29. Roy, S. H., Bonato, P., & Knaflitz M. EMG assessment of back muscle function during cyclical lifting. J Electromyogr Kinesiol. 1998;8(4):233–245.
30. Knaflitz M, Bonato P. Time-frequency methods applied to muscle fatigue assessment during dynamic contractions. 1999;9:337–50.
31. Zhang, L., Xiong, G., Liu, H., Zou, H., & Guo W. Time-frequency representation based on time-varying autoregressive model with applications to non-stationary rotor vibration analysis. Sadhana. 2010;35(2):215–232.
32. Karlsson S, Member A, Yu J, Akay M, Member S. Time-Frequency Analysis of Myoelectric Signals During Dynamic Contractions: A Comparative Study. 2000;47(2):228–38.
33. Sarililee M, Hariharan M, Anas MN, Omar MI, Oung AMNQW. Non-invasive Techniques to Assess Muscle Fatigue using Biosensors : A Review. 2014;187–92.
34. Shi J, Chang Q, Zheng Y-P. Feasibility of controlling prosthetic hand using sonomyography signal in real time: Preliminary study. J Rehabil Res Dev [Internet]. 2010;47(2):87. 35. Alty SR, Georgakis A. Mean Frequency estimation of surface EMG signals using filterbank methods. Eur Signal Process Conf. 2011;(Eusipco):1387–90.
35. Alty SR, Georgakis A. Mean frequency estimation of surface EMG signals using filterbank methods. In2011 19th European Signal Processing Conference 2011 (pp. 1387-1390). IEEE.
36. Knaflitz, M., & Molinari F. Assessment of muscle fatigue during biking. In: IEEE Transactions on neural systems and rehabilitation engineering. 2003. p. 17–23.
37. Hanon C, Thépaut-Mathieu C, Vandewalle H. Determination of muscular fatigue in elite runners. Eur J Appl Physiol. 2005;94(1–2):118–25.
38. Singh, V. P., Kumar, D. K., Polus, B., & Fraser S. Strategies to identify changes in SEMG due to muscle fatigue during cycling. J Med Eng Technol. 2007;31(2):144–151.
39. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. J Biomech. 2008;41(15):3121–6.
40. Sakurai, T., Toda, M., Sakurazawa, S., Akita, J., Kondo, K., & Nakamura Y. Detection of muscle fatigue by the surface electromyogram and its application. In: In 2010 IEEE/ACIS 9th International Conference on Computer and Information Science. 2010.
41. Ito, K., & Hotta Y. EMG-based detection of muscle fatigue during low-level isometric contraction by recurrence quantification analysis and monopolar configuration. In: In 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. 2012. p. (4237-4241).
42. Mastalerz A, Gwarek L, Sadowski J, Szczepański T. The influence of the run intensity on bioelectrical activity of selected human leg muscles. Acta Bioeng Biomech. 2012;14(2):101–7.
43. Ahamed, N., Sundaraj, K., Ahmad, R. B., Rahman, M., Islam, A., & Ali A. Non-invasive electromyography-based fatigue detection and performance analysis on m. biceps brachii muscle. In: In 2012 IEEE International Conference on Control System, Computing and Engineering. 2012. p. 302–6.
44. Tokuyasu, T., Kushizaki, S., Matsumoto, S., & Kitawaki T. Development of automatic positioning system for bicycle saddle based on lower limb’s EMG signals during pedaling motion. In: In 2013 IEEE 6th International Workshop on Computational Intelligence and Applications (IWCGIA). 2013. p. (pp. 27-32).
45. Chowdhury, R. H., Reaz, M. B. I., & Ali MAM. Determination of muscle fatigue in SEMG signal using empirical mode decomposition. In: In 2014 IEEE Conference on Biomedical Engineering and Sciences (IECBES). 2014. p. (pp. 932-937).
46. Marri, K., Jose, J., Karthick, P. A., & Ramakrishnan S. Analysis of fatigue conditions in triceps brachii muscle using sEMG signals and spectral correlation density function. In: In 2014 International Conference on Informatics, Electronics & Vision (ICIEV). 2014. p. (pp. 1-4).
47. Crozara LF, Castro A, De Almeida Neto AF, Laroche DP, Cardozo AC, Gonçalves M. Utility of electromyographic fatigue threshold during treadmill running. Muscle and Nerve. 2015;52(6):1030–9.
48. Manero RBR, Shafti A, Michael B, Grewal J, Fernandez JLR, Althoefer K, et al. Wearable embroidered muscle activity sensing device for the human upper leg. Proc Annu Int Conf IEEE Eng Med Biol Soc EMBS. 2016;2016–Octob:6062–5.
49. Ridzuan N, Azaman A, Soeed K, Zulkapri I, Aa W. Muscle Fatigue Evaluation using Non-invasive Infrared Thermography Technique With Assisted Electromyography : A Preliminary Study. 2017;251–4.
50. Mastalerz A, Urbanki C, Iwariska D, Tabor P, Karczewska-Lindinger M, Grabowska O. P 034 - the effect of treadmill geometry on muscle fatigue. Gait Posture. 2018;65(XXX):293–4.