**Convolutional neural network for needle-electromyography diagnosis in comparison with physicians: A retrospective study**

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**Abstract**

**Background**

Electromyography

**Methods and findings**

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In this study, we found that

**Author summary**

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Diagnosing neuropathy is difficult job

**What did the researchers do and find?**

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**Introduction**

Needle Electromyography (nEMG) is a type of electromyography, an electrophysiological test that records electrical activity generated from nerves, muscles, and neuromuscular junctions through a needle inserted into the muscle or surface electrode during resting and volitional state. [1-6] It is used to identify disorders of the peripheral nerves or muscles based on abnormalities in nEMG signals that reflect the anatomical and physiological characteristics of peripheral nerves and muscles. [1-6] Among the nEMG signals, the signal recorded during muscle contraction is called motor unit action potentials (MUAPs); Through this, it is possible to determine whether the subject is has neuropathy or myopathy or not. It has been known that the nEMG signals seen when examining a subject with peripheral neuropathy commonly show characteristics of large amplitudes, long durations, and reduced recruitments, whereas the nEMG signals seen when examining a patient with myopathy show characteristics of small amplitudes, short durations, and early recruitments. These differences in nEMG signals have been reported as important and useful information when diagnosing peripheral neuropathy and myopathy in previous studies. [1, 5-12]

Although nEMG plays an important role in diagnosing normal, neuropathy and myopathy, it has some limitations in that there are discrepancies among examiners, and the accuracy of nEMG relies to a lot extent on proficiency of the examiner. Previous studies have reported that sensitivity of nEMG in the diagnosis of neuropathy, myopathy, and normal is 47–83%, specificity is 73–81% and inter-rater reliability is 62–81%. [13-15] Additionally, to recognize abnormalities of nEMG signals accurately, considerable time and efforts are needed. As the prevalence of neuropathy and myopathy continues to increase, the frequency of nEMG for diagnosing it, the time it takes to interpret it, and the workload of the examiner are bound to increase. [16-19] A new approach may be helpful in clinically diagnosing neuropathy or myopathy through nEMG more efficiently and accurately in a shorter time.

Recently, deep learning has been used to analyzing big data in many field, and it is also applied to clinical data including waveform, time series data. [20, 21] Convolutional neural network, one kind of deep learning techniques, has applied to analyzing time series data and waveform data such as electrocardiography, electroencephalography. [20, 22, 23] Based on a result of the study on reading the results of electrocardiography and electroencephalography using deep learning, the accuracy was similar to or superior to that of medical students or residents, and detect nonobvious abnormalities easily overlooked. [24] Previous studies that analyzed nEMG signals using machine learning were mostly those that analyzed surface nEMG or needle nEMG signals during resting state. [25-29] To our knowledge, few studies have been reported analyzing nEMG signals during volitional state.

To overcome the limitations of nEMG, we developed a deep learning model, which are known to show good performance in image analysis. [30, 31] The development of deep learning-based nEMG analysis could lead to the development of faster and more accurate automated nEMG interpretation. We retrospectively reviewed nEMG waveforms, which were examined in subjects with peripheral neuropathy or myopathy or normal subjects, analyzed those by using convolutional neural network (CNN) algorithm, and compared the classification results of nEMG signals with classification results by 6 physicians.

**Methods**

**Study design and preparation**

In this study, nEMG signal data of 58 subjects who visited Seoul National University Hospital from June 2015 to July 2020 were used for analysis by dividing them into peripheral neuropathy, myopathy, and normal based on the final diagnosis. This study was approved by the Internal Review Board of Seoul National University Hospital (No. 2008-055-1147) and conducted according to the Declaration of Helsinki and its later amendments. Informed consent was not necessary because this study is retrospective analysis and all nEMG signal data was anonymized before analysis.

nEMG was performed with a Nicolet EDX EMG system and monopolar needle electrode from the subject’s muscles. The filter setting was set at 20 Hz (low-cut) and 10 kHz (high-cut). The results of the last 10 seconds of the nEMG were recorded and used for analysis.

The results of the waveform data of patients stored numerically in the electromyography machine were extracted, and they were made into waveform data through the MATLAB software (version R2020b). Among the created waveform data, artifacts which occurred in the cases including move of the needle electrode or patients moving, among the data at the beginning and at the end were excluded, and all of the noise in the middle portion was preserved.

The raw nEMG data, which was originally sampled at 48 kHz, was downsampled to 10 kHz to reduce computational complexity, and sliced in fixed window length of 0.4 seconds units and hop size of 0.1 seconds units that were likely to be the most optimal length for post-experimental analysis. Dataset consisted of different numbers of muscle nEMG data because the number of muscles tested was different for each subject. After slicing, total segments were composed of 2700, 3664, and 1706 segments extracted from subjects with myopathy, neuropathy, and normal subjects, respectively. Based on the elbow joint of the upper extremity and the knee joint of the lower extremity, the muscles close to this joint were classified as proximal muscles and distal muscles.

**Classification by physicians**

After senior certified neurologist and rehabilitation medicine doctor reviewed and confirmed the diagnosis of all subjects, the nEMG numerical data were extracted from EMG machine. By de-identifying the number of patient identification as a random number, the nEMG numerical data were transformed to waveform data similar to the actual result displayed on the screen of the nEMG machine; That was stored in the storage space of the web-based labeling platform so that residents belonging to different organizations can participate and provided to 2 neurology residents and 4 rehabilitation medicine residents for classification. (S1 Figure)

Six physicians classified EMG signal data without any clinical information such as symptoms or age of the subject. When the physician pressed the randomly assigned number of the subject, the EMG waveform was simultaneously played with sound and showed both real-time waveform data and waveform data stacked for 500 microseconds; Physicians were allowed to be able to change the amplitude of wave not just 100, 200, and 500 microvolts, but also 1 and 2 millivolts. Physicians first annotated the muscles, and then diagnosed the subjects by considering the results of the muscles annotation. After the physician completes diagnosis, the diagnosis was stored within the platform as well as aggregated and compared with the actual labeling.

**Classification by CNN algorithm**

Current CNN was used to sequentially classify the subject in 2 stages (S1 Figure); First, it received the nEMG signals of each muscle tested for each subject as an input and elicited one of myopathy, neuropathy, and normal as an output. Then, the final output was presented as one of myopathy, neuropathy, and normal by considering all the probability values belonging to myopathy, neuropathy, and normal of the tested muscles to the subject. The results were compared after deriving the output when only the nEMG signal was given as input without clinical information with those when both the proximal or distal and the nEMG signal, which are the location information of the tested muscle, were given as inputs.

This CNN comprised of 7 spatial reduction blocks and 5 residual blocks with 1 and 2 convolutional layers, respectively. Spatial block and residual block consisted of convolutional layers, batch normalization, and a rectified linear unit (ReLU). Hyper-parameters were determined empirically. Learning rate, batch size, and epoch was set to 10-3, 32, and 100, respectively.

**Assessing the performance of CNN algorithm**

The performance of deep learning was evaluated with the accuracy, F1 score, positive predictive value (PPV; precision), sensitivity (recall) and specificity. Since the number of subjects was small, the accuracy of this algorithm was calculated by cross entropy with 5-fold cross-validation. Based on the results of accuracy, and F1 score as well as PPV, sensitivity, and specificity, we compared the result classified by current CNN algorithm with results by physicians; also measured the degree of agreement between physicians and that between physicians and current CNN algorithm.

**Statistical analysis**

Statistical analyses were performed using R statistical software (version 4.1.0; R Foundation for Statistical Computing, Vienna, Austria) and Python 3. The differences among the groups for categorical variables were assessed using the Fisher’s exact or Pearson’s χ2 tests and those for continuous variables were assessed using the Kruskal–Wallis tests or one-way analysis of variance tests. Data are expressed as means ± standard deviation for continuous variables and number (%) for categorical variables. A *p* value less than 0.05 was regarded as statistically significant. For assessment of algorithm, an ROC (receiver operating characteristic) analysis was used with one versus other method, sensitivity plus specificity were measured with binary decision for each label, and PPV plus recall were calculated and are depicted with PPV-recall curve. Inter-rater reliability was analyzed and is expressed with value of Fleiss kappa.

**Results**

The data of the subjects used for the analysis were 20 subjects with normal and 19 subjects with neuropathy with whom the diagnosis was radiculopathy, motor axonal polyneuropathy, motor neuron disease, etc., myopathy was 19 subjects with whom the diagnosis was muscular dystrophy and inflammatory myopathy. The number of nEMG signal data used for analysis was 125, 161, and 97, respectively, length was 204.31 seconds, 423.12 seconds, and 204.31 seconds. (Table 1)

Table 1. Demographic characteristics of subjects

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Myopathy | Neuropathy | Normal | p-value |
| Number of Subjects | 19 | 19 | 20 |  |
| Female, n (%) | 14 (73.7) | 12 (63.2) | 13 (65) | 0.761 |
| Age (mean±SD) | 52.2±20.1 | 58.4±15.1 | 60.2±16.9 | 0.329 |
| Proportion of nEMG according to location of muscle (%) |  | | <0.001 | |
| Distal muscles | 60 (48.4) | 97 (60.2) | 80 (82.5) |  |
| Proximal muscles | 64 (51.6) | 64 (39.8) | 17 (17.5) |  |
| Number of nEMG (mean±SD) | 6.53±3.82 | 8.47±4.59 | 4.85±1.93 | 0.006 |
| Total signal length (sec) | 313.54 | 423.12 | 204.31 |  |

The sensitivity, specificity, and PPV of the CNN algorithm were ~, ~, ~, respectively, and the average sensitivity, specificity, and PPV of physicians were ~,~,~, respectively. (Table 2) ROC curve and PPV-recall curve is depicted. (Figure 1) The final accuracy were 76%–81% and 76%–83% with the absence of information about muscle location and without that, respectively. (Table 2)

The prediction results of muscle and subject classification by not only nEMGNet but also 6 physicians were compared. The mean accuracies of the former were 53.66% and 52.01%; those of the latter were 68.67% and 81.03%, respectively. The inter-rater reliabilities for classifying each muscle nEMG and subject nEMG between physicians were 0.258 and 0.260 expressed in Fleiss κ; the inter-rater reliability between physicians and nEMGNet were 0.249 and 0.256, respectively. (Table 2)

|  |  |  |
| --- | --- | --- |
|  | Classification results | |
|  | Physicians | CNN algorithm |
| Accuracy (%) | 0.52\* | 83.69 |
| Sensitivity (recall) |  | 0.837 |
| Specificity |  |  |
| PPV (precision) |  |  |
| F1 score |  | 0.836 |
| Area Under ROC curve |  | 0.915 |
| Inter-rater reliability (Fleiss κ) |  | |
| Overall | 0.26† | 0.26‡ |
| Myopathy | 0.36† | 0.40‡ |
| Neuropathy | 0.26† | 0.25‡ |
| Normal | 0.20† | 0.17‡ |

Table 2. The results of classification by physicians (average result of 6 physicians) and CNN algorithm. Result was shown with sensitivity, specificity, inter-rater reliability.

\*Average value of 6 physicians’ results.

† Fleiss κ value between physicians’ results

‡ Fleiss κ value between nEMGNet’s result and physicians’ results

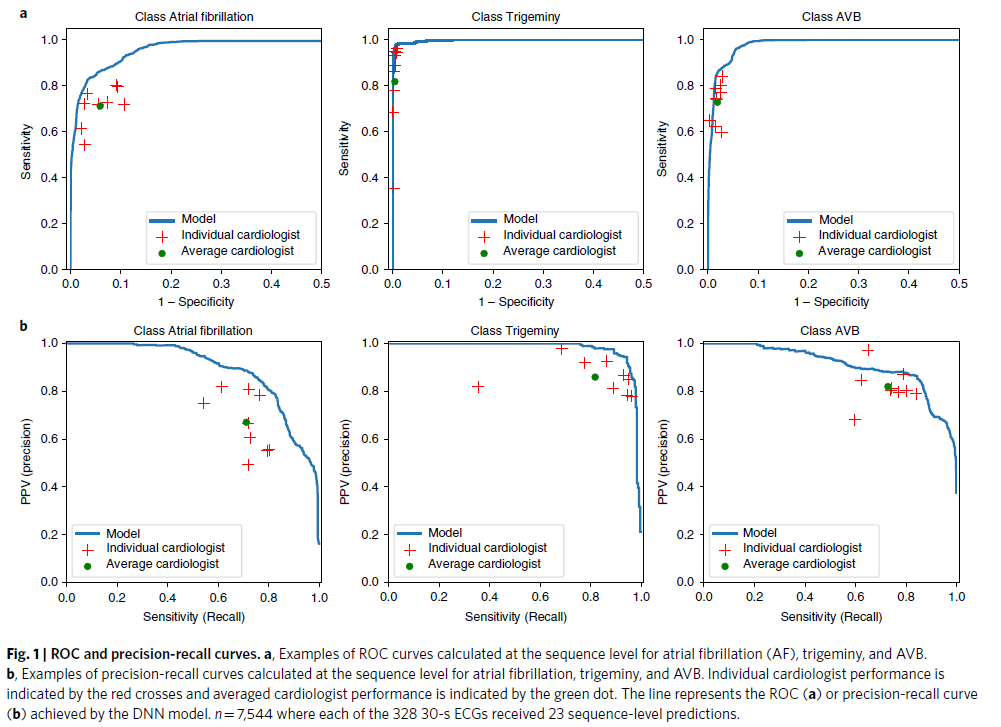


Figure 1. 예시. ROC and precision-recall curves. Neuropathy, myopathy, normal별로 추가.

The accuracies of this machine learning algorithm were calculated except missing values (n=1 for subject, n=6 for muscle signals) are depicted as confusion matrices by muscle prediction results and subject prediction results for each diagnosis. The results of measuring the prediction accuracy by group of each muscle and subject are as follows; Myopathy was 71.58%±8.06% and 81.11%±14.74%, neuropathy was 63.20%±14.09% and 80.00%±18.71%, and normal was 52.26%±21.74% and 91.11%±15.65%. (Figure 2)



Figure 2. Confusion matrices showing the accuracy of classification by current machine learning algorithm and that by physicians, excluding missing values. (n= 1 and 6, respectively) Left; Accuracy of predicted results for each nEMG waveform, Right; Accuracy of predicted results by considering all nEMG of each patient together. Physician confusion matrix추가.

Based on the results of training through nEMGNet, the characteristics of the waveform of myopathy, neuropathy, and normal were similar to characteristics of the actual nEMG waveforms. The waveform of myopathy showed small amplitude as well as short duration and counterpart of neuropathy showed high amplitude as well as long duration. (S2 Figure)



S3 Figure. Trained waveforms of myopathy, neuropathy, and normal based on nEMGNet.

(A), (C) and (E), waveform based on learned features by nEMGNet; (B), (D) and (F), actual waveform

(A) and (B), myopathy; (C) and (D), neuropathy;(E) and (F), normal.

Note that (A), (B), (E), (F) were plotted with 5mV y-axis limit and (C), (D) was plotted with 20mV y-axis limit to show the overall shape of the nEMG signal from neuropathy subjects which has characteristic of high amplitude.

**Discussion**

The aim of this study was to evaluate the accuracy of detecting the presence of peripheral neuropathy or myopathy by analyzing nEMG waveform data using machine learning, and to confirm its applicability in clinical practice. For that purpose, we applied deep learning named nEMGNet to interpreting the nEMG waveforms, and assess the performance and compare the accuracy with classification by 6 physicians. As a result of analysis with nEMGNet, the time required was shorter, and the accuracy was superior to accuracy of the physician’s analysis.

While nEMGNet is capable of extracting complex signal features, it only accepts a fixed number of signal samples. However, the number of muscles tested for each subject and the length of nEMG signal for each muscle is different. DiVote pipeline was used to overcome these limitations and contributed to the improved accuracy. Additionally, considering that peripheral neuropathy mainly shows abnormalities in the distal part muscle, whereas, myopathy mainly shows abnormalities in the proximal part muscles, addtional information on muscle location, which means whether the muscles are located close to the trunk or not, was added to the nEMGNet and this contributed to improved accuracy. Training the deep learning model with muscle type information may bias the model to make predictions based on the muscle type information, not the signals. This process was prevented by leveraging the information of muscle location in generating subject features. When creating subject features, muscle signal prediction scores were soft voted within each group divided by muscle location, and missing muscle signal prediction score was substituted with equal prediction probabilities of a third. Thus, subjects whose only proximal or distal muscles were measured are not biased during the prediction process.

Previously, there have been reports that machine learning showed good performance when applied to image analysis, surface nEMG, and needle nEMG. [25-31] Previous studies that analyzed nEMG data as 2 dimensional data using machine learning were studies to analyze gestures using surface nEMG or signals during resting state using needle nEMG. [25-29] For the purpose of diagnosing neuromuscular disorders, needle nEMG is useful rather than surface nEMG, and not only the signal during resting state but also the signal of during volitional state should be considered among needle nEMG signal. [1-6, 8, 32, 33]. After minimal noise were removed at the beginning and the end of the nEMG data, the rest nEMG data as the 1-dimensional numerical data during the volitional state for minimizing the data loss that may occur while using the 2-dimensional data as in the previous studies. To confirm the clinical applicability of nEMGNet, the diagnostic accuracy of physicians was measured and compared with that of nEMGNet. Finally, we found that the accuracy and time-taken of diagnosing neuropathy, myopathy, and normal were 83.69% and 40 seconds in using only nEMG data by nEMGNet, which is better than that of the machine learning model found in previous studies or physicians.

Interestingly, the diagnostic accuracy of physicians was lower than expected at 54%, which is thought to be due to 2 main reasons. First, in the data used in this study, the proportion of peripheral neuropathy and myopathy is out of distribution, which is much higher than the prevalence in population. Secondly, It is thought that the pre-test probability of diagnosing only with the nEMG data without clinical information such as the patient’s age and symptoms, as in clinical practice, may have worked. Additionally, when myopathy and neuropathy were classified with nEMGNet, the weight values given to proximal and distal muscles were greater in both cases. In the case of myopathy, the weight value of proximal muscle is greater than that of distal counterpart, which is usually consistent with the more common proximal involvement in myopathy. On the other hand, in the case of neuropathy, the weight value of proximal muscle is greater than that of distal counterpart, which is slightly different from the previously reported result that distal involvement is more common in neuropathy.

Out study also has some limitations. First, this study deal with retrospective data from only 1 center study. Secondly, study number is not enough to demonstrate perfect usefulness of deep learning on nEMG classification. Finally, we focused only on dividing nEMG signal into neuropathy, myopathy, and normal. However, more specialized diagnosis could be identified with more concise machine learning algorithms. Future study with much more data from multicenter will show potential of applying machine learning to nEMG interpretation.

Until now, few studies on analyzing nEMG data of volitional state by deep learning have been documented. Our study suggest that machine learning has the possibilities to be embedded in nEMG machines, reducing errors in nEMG interpretation and the workload of physicians, and potentially preventing personal medial information leakage that can arise when nEMG data is uploaded online for nEMG analysis, so shed lights on diagnosis patient of suspected neuropathy or myopathy by machine learning which might help with nEMG signal classification. Decision support의 장점도 있다.

**Contributor and guarantor information**

YIH and KKW conceptualized this work.

**Supporting information**

S1 Fig.

**References**

1. Daube JR, Rubin DI. Needle electromyography. Muscle Nerve. 2009;39(2):244-70. Epub 2009/01/16. doi: 10.1002/mus.21180. PubMed PMID: 19145648.

2. Kimura J. Electrodiagnosis in Diseases of Nerve and Muscle: Principles and Practice: Oxford University Press; 2013.

3. Mills KR. The basics of electromyography. Journal of Neurology, Neurosurgery & Psychiatry. 2005;76(suppl 2):ii32-ii5. doi: 10.1136/jnnp.2005.069211.

4. Oh SJ. Clinical Electromyography: Nerve Conduction Studies: Lippincott Williams & Wilkins; 2003.

5. Rubin DI. Needle electromyography: Basic concepts. Handb Clin Neurol. 2019;160:243-56. Epub 2019/07/07. doi: 10.1016/b978-0-444-64032-1.00016-3. PubMed PMID: 31277852.

6. Whittaker RG. The fundamentals of electromyography. Pract Neurol. 2012;12(3):187-94. Epub 2012/06/05. doi: 10.1136/practneurol-2011-000198. PubMed PMID: 22661353.

7. Aminoff MJ, Goodin DS, Parry GJ, Barbaro NM, Weinstein PR, Rosenblum ML. Electrophysiologic evaluation of lumbosacral radiculopathies: electromyography, late responses, and somatosensory evoked potentials. Neurology. 1985;35(10):1514-8. Epub 1985/10/01. doi: 10.1212/wnl.35.10.1514. PubMed PMID: 2993952.

8. Bromberg MB. The motor unit and quantitative electromyography. Muscle Nerve. 2020;61(2):131-42. Epub 2019/10/04. doi: 10.1002/mus.26718. PubMed PMID: 31579956.

9. Gerardo Gutiérrez Gutiérrez CBLFNAMM. Use of Electromyography in the Diagnosis of Inflammatory Myopathies. Reumatología Clínica (English Edition). 2012;8(4):195-200. doi: 10.1016/j.reumae.2011.10.004.

10. Leblhuber F, Reisecker F, Boehm-Jurkovic H, Witzmann A, Deisenhammer E. Diagnostic value of different electrophysiologic tests in cervical disk prolapse. Neurology. 1988;38(12):1879-. doi: 10.1212/wnl.38.12.1879.

11. Sawada K, Horii M, Imoto D, Ozaki K, Toyama S, Saitoh E, et al. Usefulness of Electromyography to Predict Future Muscle Weakness in Clinically Unaffected Muscles of Polio Survivors. PM R. 2020;12(7):692-8. Epub 2019/11/09. doi: 10.1002/pmrj.12281. PubMed PMID: 31702870.

12. Tonzola RF, Ackil AA, Shahani BT, Young RR. Usefulness of electrophysiological studies in the diagnosis of lumbosacral root disease. Ann Neurol. 1981;9(3):305-8. Epub 1981/03/01. doi: 10.1002/ana.410090317. PubMed PMID: 6261675.

13. Haig AJ, Tong HC, Yamakawa KS, Quint DJ, Hoff JT, Chiodo A, et al. The sensitivity and specificity of electrodiagnostic testing for the clinical syndrome of lumbar spinal stenosis. Spine (Phila Pa 1976). 2005;30(23):2667-76. Epub 2005/12/02. doi: 10.1097/01.brs.0000188400.11490.5f. PubMed PMID: 16319753.

14. Kendall R, Werner RA. Interrater reliability of the needle examination in lumbosacral radiculopathy. Muscle Nerve. 2006;34(2):238-41. Epub 2006/04/13. doi: 10.1002/mus.20554. PubMed PMID: 16609977.

15. Nirkko AC, Rösler KM, Hess CW. Sensitivity and specificity of needle electromyography: a prospective study comparing automated interference pattern analysis with single motor unit potential analysis. Electroencephalogr Clin Neurophysiol. 1995;97(1):1-10. Epub 1995/02/01. doi: 10.1016/0924-980x(94)00248-6. PubMed PMID: 7533715.

16. Arthur KC, Calvo A, Price TR, Geiger JT, Chiò A, Traynor BJ. Projected increase in amyotrophic lateral sclerosis from 2015 to 2040. Nature Communications. 2016;7(1):12408. doi: 10.1038/ncomms12408.

17. Longinetti E, Fang F. Epidemiology of amyotrophic lateral sclerosis: an update of recent literature. Curr Opin Neurol. 2019;32(5):771-6. doi: 10.1097/WCO.0000000000000730. PubMed PMID: 31361627.

18. Parker MJS, Oldroyd A, Roberts ME, Ollier WE, New RP, Cooper RG, et al. Increasing incidence of adult idiopathic inflammatory myopathies in the City of Salford, UK: a 10-year epidemiological study. Rheumatol Adv Pract. 2018;2(2). doi: 10.1093/rap/rky035.

19. Rose L, McKim D, Leasa D, Nonoyama M, Tandon A, Bai YQ, et al. Trends in incidence, prevalence, and mortality of neuromuscular disease in Ontario, Canada: A population-based retrospective cohort study (2003-2014). PLoS One. 2019;14(3):e0210574. doi: 10.1371/journal.pone.0210574.

20. Alfaras M, Soriano MC, Ortín S. A Fast Machine Learning Model for ECG-Based Heartbeat Classification and Arrhythmia Detection. Frontiers in Physics. 2019;7(103). doi: 10.3389/fphy.2019.00103.

21. Lu X, Wu Y, Yan R, Cao S, Wang K, Mou S, et al., editors. Pulse waveform analysis for pregnancy diagnosis based on machine learning. 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC); 2018 12-14 Oct. 2018.

22. Gemein LAW, Schirrmeister RT, Chrabąszcz P, Wilson D, Boedecker J, Schulze-Bonhage A, et al. Machine-learning-based diagnostics of EEG pathology. Neuroimage. 2020;220:117021. doi: <https://doi.org/10.1016/j.neuroimage.2020.117021>.

23. Roy Y, Banville H, Albuquerque I, Gramfort A, Falk TH, Faubert J. Deep learning-based electroencephalography analysis: a systematic review. J Neural Eng. 2019;16(5):051001. doi: 10.1088/1741-2552/ab260c.

24. Ribeiro AH, Ribeiro MH, Paixão GMM, Oliveira DM, Gomes PR, Canazart JA, et al. Automatic diagnosis of the 12-lead ECG using a deep neural network. Nature Communications. 2020;11(1):1760. doi: 10.1038/s41467-020-15432-4.

25. Akef Khowailed I, Abotabl A. Neural muscle activation detection: A deep learning approach using surface electromyography. J Biomech. 2019;95:109322. doi: <https://doi.org/10.1016/j.jbiomech.2019.109322>.

26. Atzori M, Cognolato M, Müller H. Deep Learning with Convolutional Neural Networks Applied to Electromyography Data: A Resource for the Classification of Movements for Prosthetic Hands. Front Neurorobot. 2016;10:9-. doi: 10.3389/fnbot.2016.00009. PubMed PMID: 27656140.

27. Nam S, Sohn MK, Kim HA, Kong H-J, Jung I-Y. Development of Artificial Intelligence to Support Needle Electromyography Diagnostic Analysis. Healthc Inform Res. 2019;25(2):131-8. Epub 2019/04/30. doi: 10.4258/hir.2019.25.2.131. PubMed PMID: 31131148.

28. Nodera H, Osaki Y, Yamazaki H, Mori A, Izumi Y, Kaji R. Deep learning for waveform identification of resting needle electromyography signals. Clin Neurophysiol. 2019;130(5):617-23. Epub 20190223. doi: 10.1016/j.clinph.2019.01.024. PubMed PMID: 30870796.

29. Wei W, Dai Q, Wong Y, Hu Y, Kankanhalli M, Geng W. Surface-Electromyography-Based Gesture Recognition by Multi-View Deep Learning. IEEE Trans Biomed Eng. 2019;66(10):2964-73. doi: 10.1109/TBME.2019.2899222.

30. He K, Zhang X, Ren S, Sun J, editors. Deep Residual Learning for Image Recognition. 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR); 2016 27-30 June 2016.

31. Simonyan K, Zisserman A. Very Deep Convolutional Networks for Large-Scale Image Recognition. arXiv 14091556. 2014.

32. Haig AJ, Gelblum JB, Rechtien JJ, Gitter AJ. Technology assessment: the use of surface nEMG in the diagnosis and treatment of nerve and muscle disorders. Muscle Nerve. 1996;19(3):392-5. doi: 10.1002/(sici)1097-4598(199603)19:3<392::Aid-mus21>3.0.Co;2-t. PubMed PMID: 8606710.

33. Meekins GD, So Y, Quan D. American Association of Neuromuscular & Electrodiagnostic Medicine evidenced-based review: use of surface electromyography in the diagnosis and study of neuromuscular disorders. Muscle Nerve. 2008;38(4):1219-24. doi: 10.1002/mus.21055. PubMed PMID: 18816611.