**Deep learning model for needle electromyography**

**electrodiagnosis in comparison with physician assessment:**

**A retrospective study**

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**Abstract**

**Background**

Electromyography (EMG) plays an important role in the diagnosis of neuromuscular diseases by identifying the characteristic abnormalities of the waveform. However, it has some limitations in that there are discrepancies in the interpretations of electrodiagnosis results among physicians, and the accuracy of electrodiagnosis using EMG relies on the experience of physicians. To overcome these limitations of EMG, we investigated whether the deep-learning approach can better classify EMG waveforms into neuropathy, myopathy, and normal physicians’ electrodiagnosis results.

**Methods and findings**

Needle EMG data (58 patients, 382 muscles) from the Seoul National University Hospital database from June 2015 to July 2020 were used. A one-dimensional convolutional neural network model was used as the deep-learning model. The deep-learning model and the six physicians classified and electro-diagnosed the EMG waveforms as myopathy, neuropathy, or normal.

The accuracy, sensitivity, specificity, positive predictive value and F1 score of the deep learning model were 0.720, 0.715, 0.858, 0.726, and 0.715, respectively, and the physicians’ mean scores were 0.537, 0.527, 0.770, 0.582, and 0.511, respectively. The performance of the deep-learning model for predicting myopathy, neuropathy, and normal was also evaluated using the area under the receiver operating characteristic curve, and the results were 0.874 (95% confidence interval [CI] 0.858–0.889), 0.781 (95% CI 0.723–0.839), and 0.847 (95% CI 0.836–0.858), respectively.

**Conclusions**

This study demonstrated that deep-learning could contribute to interpreting the EMG of patients with neuromuscular disease on behalf of physicians and assist physicians’ decision-making regarding diagnosing patients with neuromuscular disease. Large prospective cohort studies with more diverse neuromuscular diseases will further improve the performance of deep-learning-based EMG interpretation in the future.

**Keywords**: Electromyography, Machine learning, Neuromuscular disease, Deep learning, Convolutional neural network**Author summary**

**Why was this study done?**

* Electromyography (EMG) is an important electrophysiological test that is widely performed when diagnosing patients with neuromuscular disease.
* Despite the importance of EMG in diagnosis, the accuracy of EMG electrodiagnosis is not sufficiently precise, and there are often discrepancies among examiners. Therefore, a more objective and accurate method of EMG analysis is required.
* Although EMG in volitional state plays important role in diagnosing neuromuscular disease, previous studies have mainly focused on analysis of gestures using surface EMG or analysis of the abnormal spontaneous activities from needle EMG during resting state. Therefore, additional research is needed for clinical application of deep learning-based electrodiagnosis of neuromuscular disease.

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

* The EMG data from 58 patients were used in this study. Patients were classified by the deep-learning model and were electro-diagnosed by the physicians as myopathy, neuropathy, or normal. After classification and electrodiagnosis, the classification results of the deep-learning model were compared with the electrodiagnosis results obtained by neurologists and rehabilitation medicine doctors.
* The accuracy of classifying EMG data using our deep-learning model was 0.720, and the average accuracy of electrodiagnosis by physicians was 0.537.
* Classification using our deep-learning model was more accurate and faster than electrodiagnosis by physicians.

**What do these findings mean?**

* Deep-learning can electrodiagnose EMG on behalf of a physician and can be used to assist physicians in diagnosing patients with neuromuscular disease.
* The performance of deep-learning could be further enhanced by conducting large-scale prospective study that includes patients with more diverse and specific types of neuromuscular diseases.

**Introduction**

Electromyography (EMG) is 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 states [1-6]. Disorders of the peripheral nerves and muscles are identified with the abnormalities in EMG signals, which reflect the anatomical and physiological states of peripheral nerves and muscles [1-6].

The signal recorded during muscle contraction, consists of motor unit action potential (MUAP) which can only be measured from muscles in a volitional state not in a resting state. Since EMG signals during a resting state cannot contribute to distinguishing between neuropathy and myopathy, MUAP is an essential key in distinguishing whether a patient has neuropathy or myopathy [1, 5-12]. Additionally, when the neuromuscular disease is in the early state or in a mild abnormal state, abnormal findings are found only in MUAP during a volitional state not during in a resting state [13, 14]. A patient with peripheral neuropathy commonly shows MUAP with high amplitudes, long durations, and reduced recruitments, whereas one with myopathy commonly exhibits MUAP with small amplitudes, short durations, and early recruitments on the EMG evaluation [1, 5-12]. Needle EMG (nEMG) is a type of EMG that uses needle as an electrode and is useful for recording the MUAPs from individual motor units and deep muscles [15].

Although EMG plays an important role in diagnosing normal, neuropathy or myopathy of a patient, there are some limitations. First, the accuracy of EMG diagnosis relies on the proficiency of the examiner. Previous studies have reported that sensitivity of EMG in the diagnosis of neuropathy, myopathy, and normal is 47–83%, specificity is 73–81% and inter-rater reliability is 62–81% [16-18]. Second, considerable time and effort is needed to abnormalities of EMG signals accurately. The prevalence of neuropathy and myopathy continues to rise which burdens physicians with increased number of EMG waiting to be electro-diagnosed. [19-22]. An accurate, efficient, and automated approach may be helpful in clinical diagnosis using the nEMG.

Recently, a deep-learning has been used to analyzing big data in many fields, and it is also applied to clinical data including waveform, time series data such as electrocardiography and electroencephalography [23-26]. There have also been number of studies on deep-learning in medical applications which the performance of the deep-learning model was similar to or better than that of humans [27-30]. In previous studies on EMG, machine learning has been mainly used to analyze the abnormal spontaneous activities that is present on EMG during resting state or the gestures that are not related to the diagnosis of neuromuscular diseases using surface EMG [31-35]. To the best of our knowledge, few studies have been reported using machine learning to analyze nEMG signals during a volitional state.

To overcome the diagnostic limitations of EMG and investigate the feasibility of machine learning on nEMG during a volitional state, we developed a deep-learning model that could classify the patient into myopathy, neuropathy or normal based on volitional state-nEMG signals. We retrospectively reviewed nEMG data of patients with peripheral neuropathy or myopathy as well as patients without any neuromuscular disease. The classification results by out deep-learning model and electrodiagnosis results by 6 physicians were compared.

**Methods**

**Study design and preparation**

The nEMG signal data consisted of 58 patients who visited Seoul National University Hospital from June 2015 to July 2020. Each patient was labeled with one of peripheral neuropathy, myopathy, and normal based on the final diagnosis. This study was approved by the institutional review board of Seoul national university hospital (No. 2008-055-1147), and was conducted according to the Declaration of Helsinki and its later amendments. Informed consent was not necessary because this study was retrospective analysis and private information from all patients were anonymized before analysis.

The nEMG evaluation was performed with a Nicolet EDX EMG system and a monopolar needle electrode. The filter setting was set at 20 Hz (low-cut) and 10 kHz (high-cut). The nEMG signal was measured at sampling rate of 48 kHz. The results of the final 10 seconds during the nEMG were stored in EMG machine and used for analysis.

The certified neurologist and the certified rehabilitation medicine doctor reviewed the nEMG data and confirmed the diagnosis of all patients. After extracting the nEMG signal stored as numerical data in the EMG device, it was converted into waveform data using MATLAB software (version R2020b). Among the created waveform data, electromyographic artifacts which occurred from the movement of the needle electrode or the patient, were removed at the beginning and at the end of EMG data. The noise in the rest of the data was preserved. Based on the elbow joint of the upper extremity and the knee joint of the lower extremity, muscles close to the trunk were labeled as proximal muscles and those far from the trunk as distal muscles.

**Electrodiagnosis by physicians**

A web-based nEMG signal labeling platform was developed to allow residents, who belonged to different institutions, electro-diagnose patients of this study. After de-identifying the patient information, the nEMG waveform data were displayed on the screen in a similar way the EMG data presented on the EMG device (S1 Fig).

Two residents of neurology and four residents of rehabilitation medicine watched the nEMG signal of the muscles examined for each patient and electro-diagnosed the patient as one of myopathy, neuropathy, and normal without clinical information other than nEMG results. When the physician clicked the anonymized patient id, the nEMG waveform data was presented on the screen along with the sound similar to the sound from the EMG device. The real-time waveform data was presented on the left, and the waveform data was stacked on the right for 500 microseconds. The physicians were allowed to change the voltage amplitude ticks of the screen among 100 μV, 200 μV, 500 μV, 1 mV, and 2 mV. Physicians first annotated each nEMG signal from different muscles, and then diagnosed the patients by considering the muscles annotation results. The electrodiagnosis results of physicians were stored within the platform.

**Classification by deep-learning model**

The nEMG signals were down-sampled to 10 kHz to reduce computational complexity. Each data was partitioned into windowed segments with lengths of 0.4 second and hop sizes of 0.1 second. The length and the hop size of the windows were selected heuristically. After slicing, there were total of 3664, 2700, and 1706 segments from patients with neuropathy, myopathy, and normal patients, respectively.

A one-dimensional convolutional neural network (CNN) was used as the deep-learning model [36]. The CNN was designed after the motives of ResNes and VGG, which are well-performing image classification models [37, 38]. The CNN comprised of 7 spatial reduction blocks, 5 residual blocks, and fully connected layers (S2 Fig). The spatial reduction block consisted of convolutional layers, batch normalization, rectified linear unit (ReLU), and max pooling. The residual block contained similar layers with an added residual connection [37]. The fully connected layers consisted of 512, 256, 64, 16 hidden layer neurons, with leaky ReLU activation function. The softmax function was applied to the final three-output layer. The model receives raw signal segments and predicts the three class (myopathy, neuropathy, normal) probabilities.

Hyper-parameters were determined empirically with learning rate of 10-3, batch size of 32, and epoch of 100. Early stopping was performed by evaluating accuracy on the validation set every 30 updates, and the patience value was set to 100 [39]. Cross entropy loss was used as the loss function with class weights applied inverse proportionally to the number of signal segments from the train set. Deep-learning performance was measured through 5\*3-fold cross validation (5\*3 CV) since there were small number of subjects.

The deep-learning model used two stages to classify the patient; first, it received the multiple segments sliced from a single muscle’s nEMG data and returns the three-class probability of the segment being myopathy, neuropathy, or normal. The probabilities of the segments were averaged to produce a three-class probability of each muscle. After probabilities of all muscle from each patient are computed, feature vector was produced for the patient using the individual muscle probabilities. Two methods were compared to generate the feature vector. Another method was to average the muscle probabilities per muscle location label (proximal muscle or distal muscle) to produce six-dimensional vector. When patient did not have any muscle probability for some muscle location label, mean value of 1/3 was imputed to prevent undesired bias. The performance of deep-learning model presented in this article are from averaging over all muscle probabilities. The second stage receives the feature vector generated and classifies the three-class diagnosis of the subject using a logistic regression classifier.

After the model was trained, an explainable artificial intelligence technique named feature visualization was applied to visualize the features which the model is focusing on [40]. The initial feature was sampled from gaussian distribution N (0,0.5), and random jitter was applied as regularization with 12.5% of the signal segment length. Learning rate was 10-2 and gradient descent updates were applied 3000 times.

**Assessing the results of the deep-learning model and the physicians**

The performances of the deep-learning model and the physicians were evaluated with following metrics: accuracy, F1 score, area under receiver operating characteristic curve (AUROC), positive predictive value (PPV; precision), sensitivity (recall), and specificity. Based on those metrics, we compared the result classified by two versions of deep leaning model with and without muscle location labels and averaged result by six physicians.

**Statistical analysis**

Statistical analyses were performed using R statistical software (version 4.1.0; R Foundation for Statistical Computing, Vienna, Austria) and Python programming language (version 3.6). The normality for continuous variables was assessed using the Shapiro-Wilk test. The differences among the groups for categorical variables were assessed using the Pearson’s χ2 test and those for continuous variables were assessed using the Kruskal–Wallis test. Data are expressed as means ± standard deviation for continuous variables and number (%) for categorical variables. The degree of agreement was calculated within physicians and the deep-learning model, and is expressed with value of Fleiss kappa. All metrics except accuracy (F1 score, AUROC, PPV, recall, and specificity) were binary classification, so were measured by averaging each class metrics from one-versus-rest method.

**Results**

**Patients’ characteristics**

There were total of 20 patients without any neuromuscular disease, 19 patients with neuropathy including radiculopathy, motor axonal polyneuropathy, and motor neuron disease, and 19 patients with myopathy including muscular dystrophy and inflammatory myopathy. The number of nEMG data used for analysis was 124, 161, and 97 for myopathy, neuropathy, and normal, respectively. The rest of demographic characteristics are shown in Table 1.

Table 1. Demographic characteristics of patients and their needle electromyography data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Myopathy | Neuropathy | Normal | p-value |
| Number of patients | 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 |
| Number of nEMG data 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 |  |

nEMG=needle electromyography

data are expressed in mean±standard deviation.

**Performance results of deep-learning and physicians**

The classification performance of deep-learning algorithm was compared to electrodiagnosis results of physicians using following metrics: the accuracy, sensitivity, specificity, PPV, and F1 score. Sliced segments less than 0.4 seconds were excluded because the deep leaning model only receives segment longer than 0.4 seconds; total of 8 patients and 10 muscle nEMG data were excluded from analysis because these were not annotated by either the physicians or the deep-learning model. The results of the deep-learning model that did not use muscle location information are presented as the above-mentioned metrics: the accuracy, sensitivity, specificity, PPV, and F1 score are 0.720±0.040, 0.715±0.050, 0.858±0.023, 0.726±0.032, and 0.715±0.044, respectively. The counterparts of physicians were 0.537±0.069, 0.527±0.069, 0.770±0.034, 0.582±0.076, and 0.511±0.084, respectively (Table 2), The degree of agreement, expressed in Fleiss κ, between physicians was 0.26 and between physicians and deep-learning model was 0.26 (S1 Table).

Table 2. The electrodiagnosis results by physicians and classification results by the deep-learning model

|  |  |  |
| --- | --- | --- |
|  | Physicians (95% CI) | Deep-learning model (95% CI) |
| Accuracy | 0.537 (0.491–0.583)\* | 0.811 (0.682–0.758)† |
| Sensitivity (recall) | 0.527 (0.480–0.573)\* | 0.720 (0.668–0.762)† |
| Specificity | 0.770 (0.747–0.793)\* | 0.853 (0.836–0.879)† |
| Posivie predictive value (PPV, Precision) | 0.582 (0.530–0.633)\* | 0.725 (0.695–0.757)† |
| F1 score | 0.511 (0.455–0.568)\* | 0.715 (0.673–0.757)† |

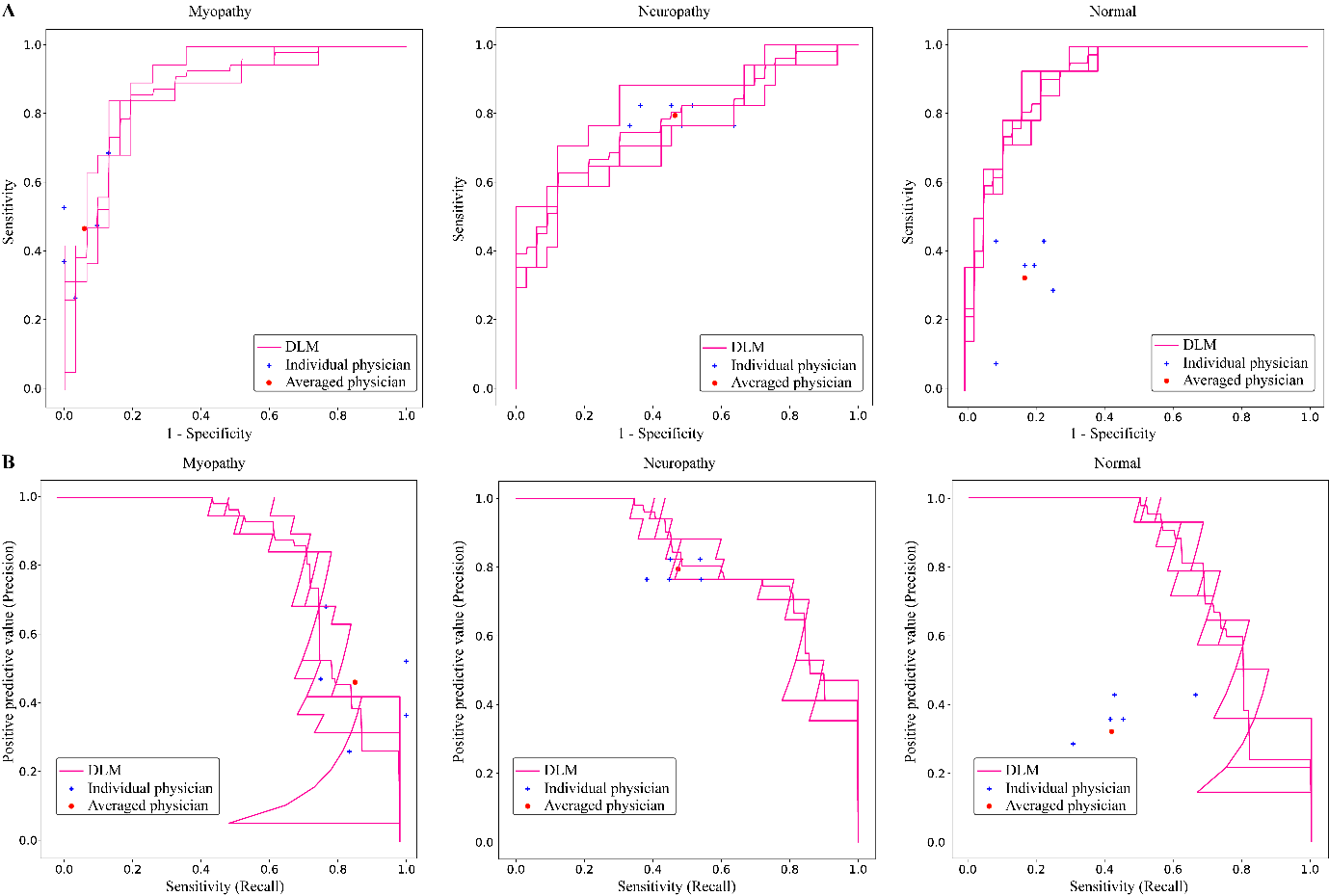
\* Average results of electrodiagnosis by 6 physicians

† Average results of classification by 3 deep-learning models

The metrics except for accuracy are average of binary classification scores for each class from one-versus-rest method.

95% CI=95% confidence interval

Per-class ROC curves and precision-recall curves of the deep-learning model were measured and depicted; for comparison, electrodiagnosis results of individual physician and averaged physician were measured and depicted in terms of sensitivity, specificity, and positive predictive value on Fig 1. The per-class physicians results for myopathy and neuropathy were placed near ROC curve and precision-recall curve of the deep-learning model. The deep-learning model outperformed when classifying normal patients. The AUROC of deep-learning model classification result per class was 0.874 (95% confidence interval [CI] 0.858–0.889), 0.781 (95% CI 0.723–0.839), and 0.906 (95% CI 0.899–0.913) for myopathy, neuropathy, and normal, respectively.

Fig 1. Per-class receiver operating characteristic and precision-recall curves of the deep-learning model and six physicians

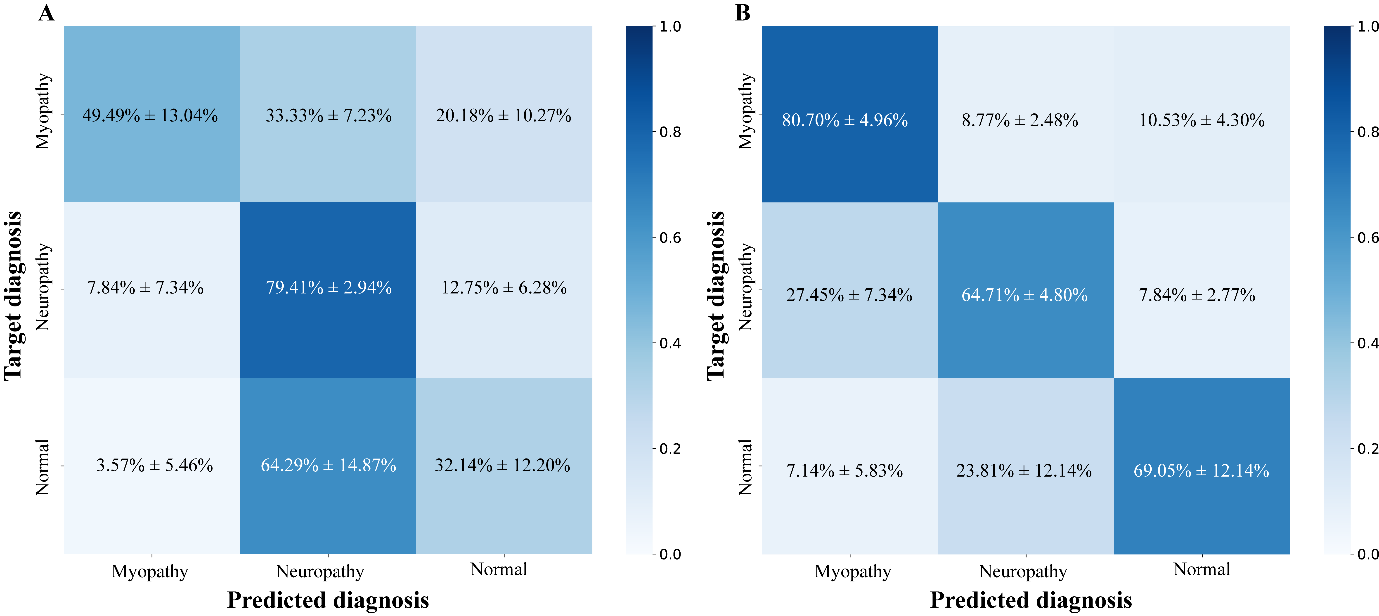
DLM= Deep-learning model

A. Area under receiver operating characteristic curve (A) and precision-recall curve (B) was measured and depicted by dividing all data into myopathy, neuropathy, and normal.

Individual physician performance is annotated by the blue cross and averaged physician performance is annotated by the red dot.

From the confusion matrix of physicians and the deep-learning model, the overall prediction pattern was identified (Fig 2). The correctly predicted ratios for myopathy, neuropathy, and normal by the deep-learning model were 80.70%±4.96%, 64.71%±4.80%, and 69.05%±12.14%, respectively; the correctly electro-diagnosed ratios for myopathy, neuropathy, and normal by the physicians were 49.49%±13.04%, 79.41%±2.94%, and 32.14%±12.20%, respectively. The deep-learning model outperformed physicians in predicting myopathy and normal, and not in predicting neuropathy.

Fig 2. Confusion matrices of (A) physician electrodiagnosis results and (B) the deep-learning model prediction results



**Performance of the machine learning model considering the muscle location information**

The performances of deep-learning model did not change significantly when muscle location information was added. The accuracy, sensitivity, specificity, PPC, and F1 score of the deep-learning model considering the muscle location information were 0.700±0.053, 0.698±0.048, 0.848±0.026, 0.703±0.058, and 0.694±0.049, respectively (S2 Table). The AUROC of the same deep-learning model were 0.841 (95% CI 0.811–0.871), 0.736 (95% CI 0.731–0.741), and 0.792 (95% CI 0.719–0.864) for myopathy, neuropathy, and normal, respectively (S3 Fig). The correctly predicted ratios for myopathy, neuropathy, and normal were 80.70%±8.95%, 54.90%±2.77%, and 73.81%±3.37%, respectively (S4 Fig). From the The prediction accuracies of CNN with muscle location information and those of CNN without muscle location information were as follows; the former and latter results for myopathy, neuropathy, and normal were 80.70%±8.95%, 54.90%±2.77%, 73.81%±3.37%, and 80.70%±4.96%, 64.71%±4.80%, 69.05%±12.14%, respectively (S4 Fig).

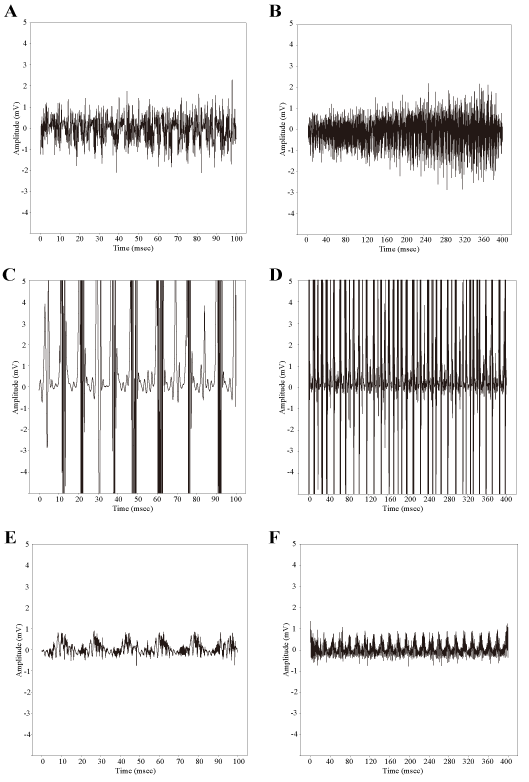
**Mispredicted cases of the deep-learning model**

In order to analyze the reason why the deep-learning model misclassified, we reviewed the misclassified nEMG signals. The examples of those are shown in S5 Fig.

**Learned features of the deep-learning model**

The learned features of the deep-learning model were identified from created signals by applying feature visualization. The created signals were similar to the typical characteristics of neuropathy, myopathy, and normal. The waveform most likely to be predicted as myopathy and neuropathy showed small amplitudes as well as short durations (Fig 3A,B) and high amplitudes as well as long durations, respectively (Fig 3C,D). Thus, we validated that the deep-learning model had made predictions based on relevant features not artifacts.

Fig 3. Feature visualization results of the deep-learning model



A and B, Myopathy; C and D, Neuropathy; E and F, Normal.

Note that A, C, E were plotted with 10 milli seconds of x-axis interval and B, D, F were plotted with 40milli seconds of x-axis interval to show the recruitment and interference pattern of overall waveforms.

**Discussion**

The aim of the present study was to validate the diagnostic performance of the machine learning using nEMG signals in a volitional state whether machine learning could support physician’s decision for more accurate and efficient diagnosis. For that purpose, deep-learning was used to classify the nEMG signals into myopathy, neuropathy, and normal; and the classified results were compared with electrodiagnosis results by six physicians. Results demonstrated that our deep-learning model outperformed electrodiagnosis results of physicians in all performance scores, including the accuracy which was 0.720±0.040 for the deep-learning model and 0.537±0.069 for the physicians.

There have been reports that machine learning showed good performance when applied to analyzing EMG signals [31-35]. However, previous studies on EMG have been mainly focused on abnormal spontaneous activities in a resting state, and the signals were preprocessed to form two-dimensional features which may increases computational complexity [33, 34]. It has been well known that the EMG evaluation is important in the diagnosis of the neuromuscular disease; and EMG signals during a volitional state play an essential role in differentiating myopathy, neuropathy, normal as well as identifying the neuromuscular disease in the initial state or the minimally involved state [1-6, 8, 13, 14, 41]. To the best of our knowledge, there have been few studies that analyze the EMG data during a volitional state using a deep-learning. We analyzed nEMG signal in volitional state, which is important for electrodiagnosis of neuropathy and myopathy, and confirmed that it showed better performance than physicians.

In order to finally diagnose a patient, the nEMG results of all tested muscles should be considered altogether. However, not all nEMG signals from muscles show abnormalities and the number of muscles examined may be slightly different for each patient, so this variation needs to be considered for the deep-learning model. To solve these variation problem, we constructed feature vectors for patients from muscle signal prediction probabilities and utilized an additional classifier to determine the classification result of the patient. This method allows the deep-learning model not only to consider all the signals measured from different muscles from different patients in a consistent format but also to make predictions based on the signal characteristics, and not on the prevalence of nEMG signals in certain type of muscles.

Usually, there are typical pattern of muscle involvement that peripheral neuropathy mainly show abnormalities in the distal muscles, whereas myopathy mainly show abnormalities in the proximal muscles [13]. Although muscle location information is meaningful for differentiating neuropathy and myopathy, there was no significant change in the performance of the deep-learning model when muscle location information was used; this is thought to be due to following two reasons. First, some types of myopathy may show abnormalities in both proximal and distal muscles. For instance, in muscular dystrophy, the distribution of the affected muscle depends on the disease process. In statin induced myopathy and critical illness myopathy, both proximal and distal muscles are affected. Myotonic dystrophy type 1,2 or distal myopathy may affect distal muscles more frequently than proximal muscles [13, 42, 43]. Second, the small number of patients may be insufficient to generate significant features within the muscle location information.

Among the misclassified signals by the deep-learning model, several examples were inspected (S5 Fig). Signals that contain parts with high amplitude were misclassified as neuropathy (S5A,D Fig), and signals that contain parts with small amplitudes were misclassified as myopathy (S5B,C Fig). From the feature visualization results of the trained deep-learning model, it was identified that deep-learning model makes predictions by amplitude, duration, recruitment, and interference pattern of typical myopathy, neuropathy, and normal patients. Thus, the amplitudes of mispredicted nEMG signals may dominated the recruitment and interference patterns which lead the deep-learning model to predict incorrectly.

Interestingly, the diagnostic accuracy of physicians was 0.537 which lower than expected. This low accuracy is accounted for 2 following reasons. First, our data included 40 patients with neuromuscular disease out of a totel of 60 patients, which is much more than the real prevalence of approximately 200 per 100,000 population [44]. Second, the electrodiagnosis of the physicians during this study was different from the real-world diagnosis process. Physicians consider nEMG signals as well as additional information about the patient such as demographics or symptoms, which were absent in the labeling platform.

There were several limitations of this study. First, this study used retrospective data from a single institution. When additional data from other institutions are available, external validation could be performed to further verify the model performance. Second, larger amount of nEMG data needs to be examined to demonstrate the stable performance of deep-learning on nEMG classification. The 58 patients from this study are not enough to demonstrate the perfect usefulness of this deep-learning model and larger cohort may elicit useful information from the muscle location as well. Third, the patient diagnosis label were crudely divided into neuropathy, myopathy, and normal. There are diverse subtypes of neuromuscular diseases such as chronic inclusion body myositis, ongoing-state dermatomyositis, and late-stage muscular dystrophy, which co-exhibit MUAPs of myopathy and neuropathy, which have short duration and long duration. Additional nEMG data with more specific neuromuscular disease could improve the usefulness of deep-learning to nEMG clinical assistance. Finally, resting state nEMG data may be added for better prediction. In some neuromuscular diseases such as Pompe disease, EMG abnormalities may be revealed only in the resting state of the paraspinal muscles rather than the limb muscles [13, 45]. Future prospective study with resting and volitional state EMG data could further improve the applicability of deep-learning in EMG electrodiagnosis.

Few studies have documented on analyzing nEMG signals in a volitional state using deep-learning. Results from this study demonstrated that deep-learning could analyze nEMG signals in short time and high accuracy, and our relatively simple model has the potential to be embedded in nEMG device. Embedding a fast, accurate, and simple machine learning model into nEMG machine could allow clinical assistance within the device without sharing personal medical information. Such application could not only reduce the burden of physicians, but lead to widely applicable, low-cost clinical decision system to be used in small medical institutions.

In summary, our study presented significant potentials that deep-learning may contribute to automatic computer-aided electrodiagnosis system of patients with neuromuscular diseases.

**Supporting information**

S1 Fig. Electromyography labeler platform



A web-based labeling platform named ‘EMG Labeler’. nEMG signals were presented in a similar way the signals are presented from the EMG device

S1 Table. Degree of agreement between physicians and the deep-learning model\*

|  |  |  |
| --- | --- | --- |
|  | Physicians | Deep-learning model |
| Overall | 0.260† | 0.256‡ |
| Myopathy | 0.360† | 0.400‡ |
| Neuropathy | 0.256† | 0.247‡ |
| Normal | 0.204† | 0.165‡ |

\* data are expressed in Fleiss κ

† Fleiss κ value between the results by 6 physicians

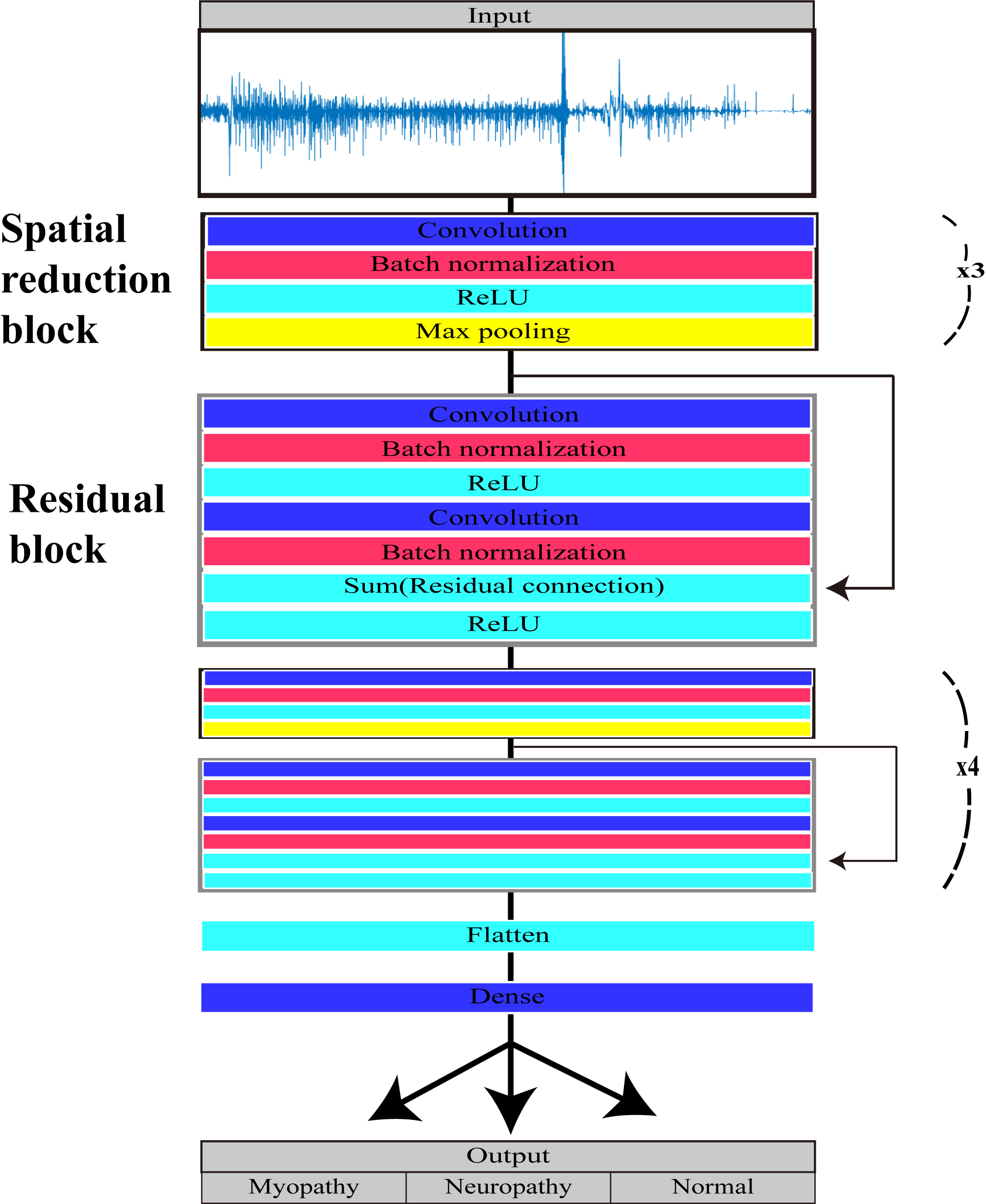
‡ Fleiss κ value between the results by 6 physicians and deep-learning model

S2 Table. Classification results by the deep-learning model with and without muscle location information

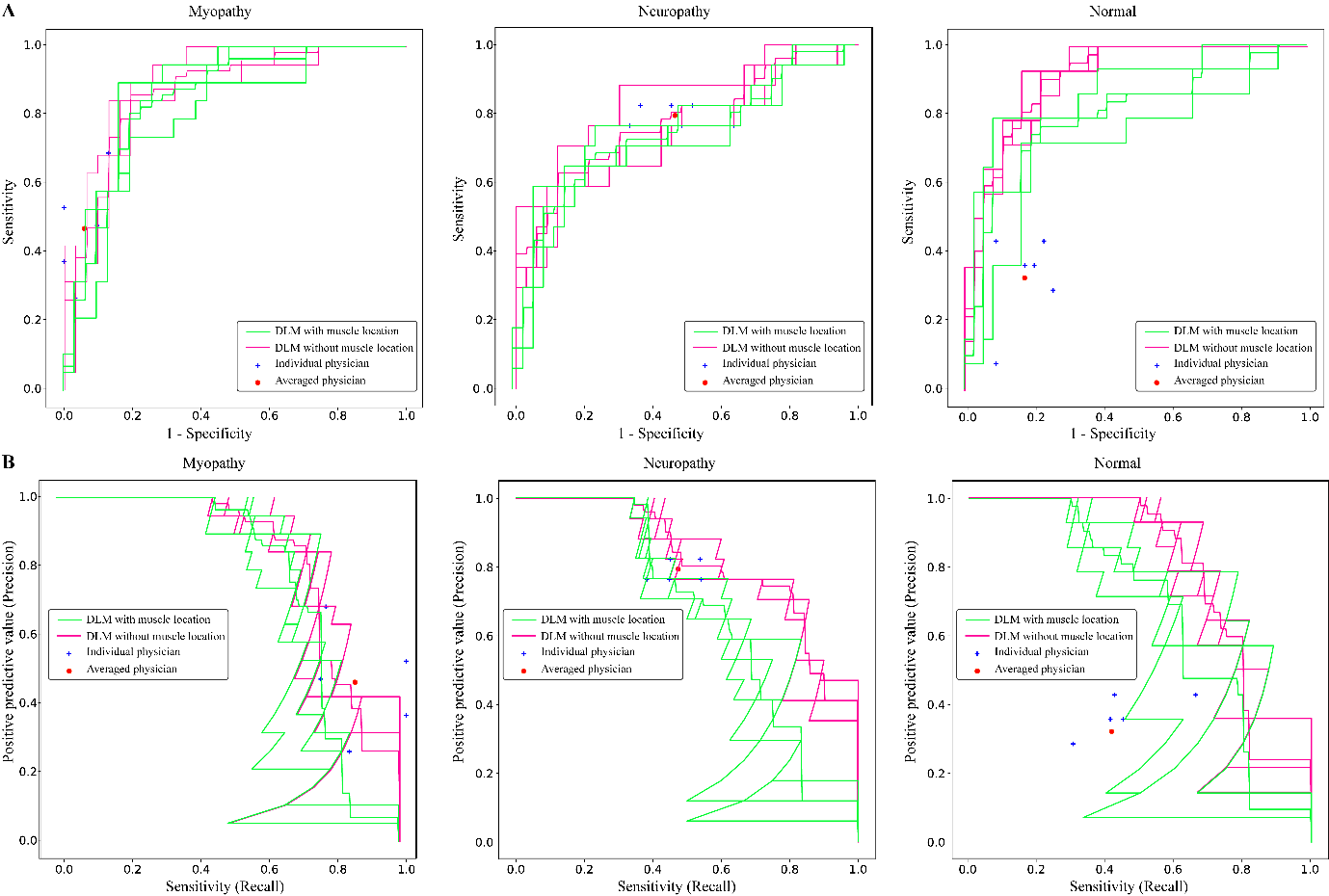
|  |  |  |
| --- | --- | --- |
|  | Performance results (95% CI) | |
|  | Without information | With information |
| Accuracy | 0.720 (0.682–0.758) | 0.700 (0.650–0.750) |
| Sensitivity (recall) | 0.715 (0.668–0.762) | 0.698 (0.652–0.744) |
| Specificity | 0.858 (0.836–0.879) | 0.848 (0.824–0.873) |
| Positive predictive value (PPV, precision) | 0.726 (0.695–0.757) | 0.703 (0.648–0.758) |
| F1 score | 0.715 (0-.673–0.757) | 0.694 (0.647–0.741) |

CI=Confidence interval

The average metrics of the classification results by 3 deep-learning models are presented. The metrics except for accuracy are average of binary classifications cores for each class from one-versus-rest method.

S Fig. Structure of the deep-learning model

There are 7 spatial reduction blocks and 5 residual blocks with 1 and 2 convolutional layers, respectively

S Fig. Per-class receiver operating characteristics and precision-recall curves of the machine learning model with and without the muscle location information

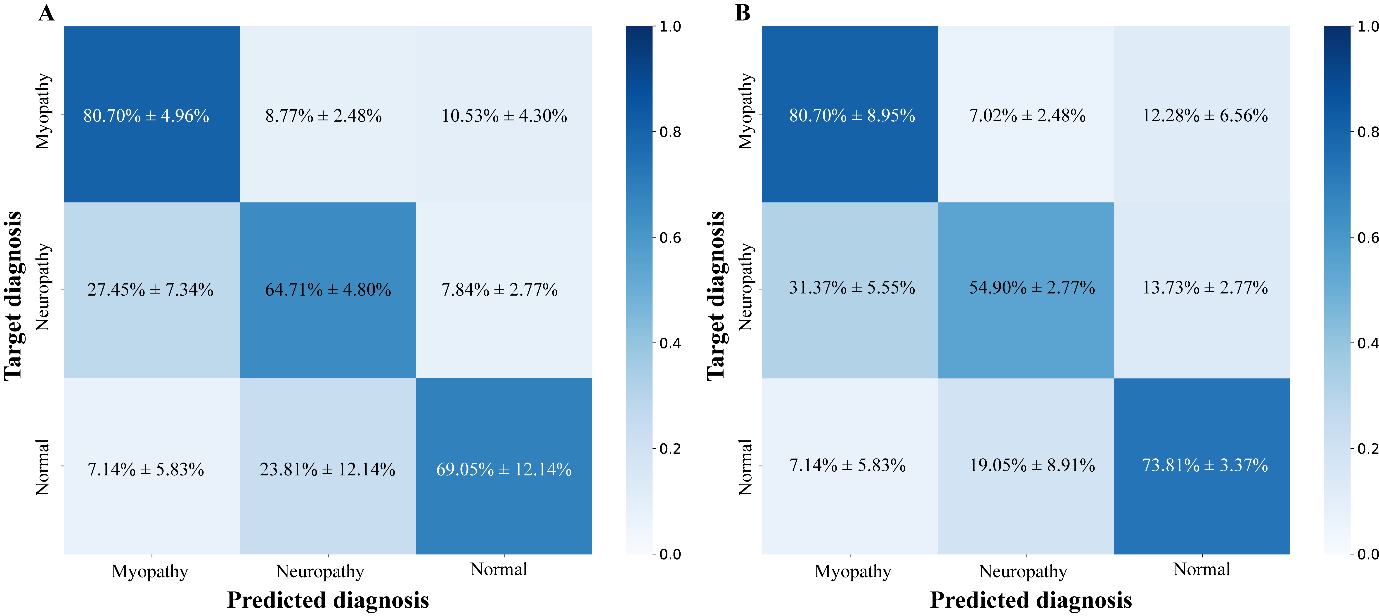
DLM = Deep-learning model

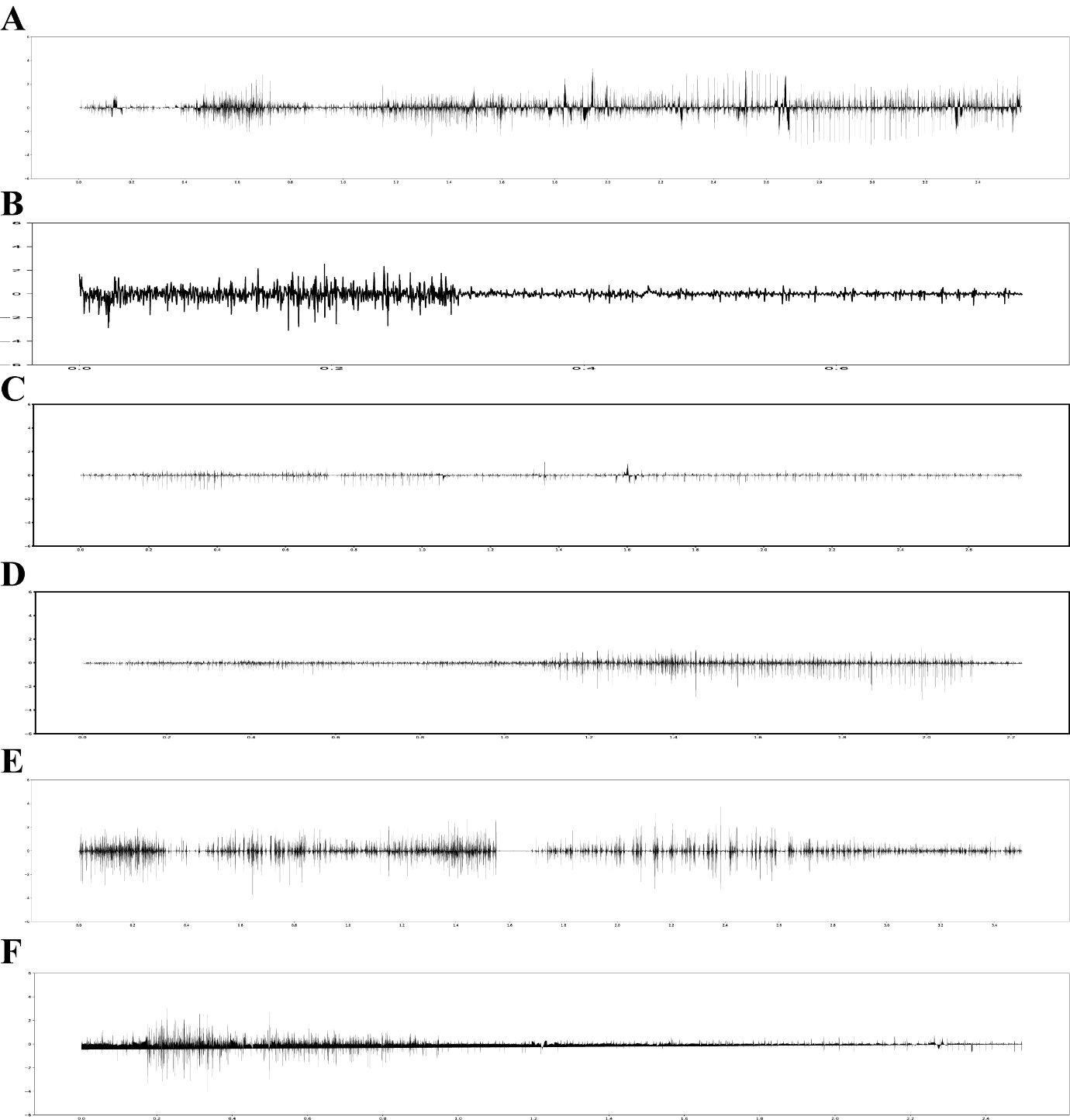
The area under receiver operating characteristic curves (A) and precision-recall curves (B) were measured and depicted by dividing all data into myopathy, neuropathy, and normal.

Individual physician performance is annotated by the blue cross and averaged physician performance is annotated by the red dot.

ROC and precision-recall curves of the convolutional neural network algorithm depending on whether the muscle location information was considered (green lines, CNN with muscle location) or not (pink lines, CNN without muscle location).

S Fig. Confusion matrices of the machine learning model (A) without muscle location information and (B) with muscle location information



S Fig. Examples of electromyographic signals mispredicted by the deep-learning model

Electromyographic signal mispredicted (A) normal to neuropathy, (B) normal to myopathy, (C) neuropathy to myopathy, (D) neuropathy to normal, (E) myopathy to neuropathy, (F) myopathy to normal

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**Abbreviations**

nEMG, needle electromyography; CNN, convolutional neural network; CI, confidence interval; EMG, electromyography; ReLU, rectified linear unit; AUROC, area under receiver operating characteristic curve; PPV, positive predictive value; ROC, receiver operating characteristic

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