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Feasibility of Sarcopenia Diagnosis Using Stimulated Muscle Contraction Signal in Hemiplegic Stroke Patients

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HIGHLIGHTS

- Sarcopenia can be classified using stimulated muscle contraction signals (SMCS).
- SMCS represent the response signals of motor neurons and muscle fibers.
- SMCS could be ideal for sarcopenia screening in stroke patients.

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ABSTRACT

Sarcopenia, a condition characterized by muscle weakness and mass loss, poses significant risks of accidents and complications. Traditional diagnostic methods often rely on physical function measurements like handgrip strength which can be challenging for affected patients, including those with stroke. To address these challenges, we propose a novel sarcopenia diagnosis model utilizing stimulated muscle contraction signals captured via wearable devices. Our approach achieved impressive results, with an accuracy of 93% and 100% in sarcopenia classification for male and female stroke patients, respectively. These findings underscore the significance of our method in diagnosing sarcopenia among stroke patients, offering a non-invasive and accessible solution.

Keywords: Sarcopenia; Stroke; Electrical Stimulation; Muscle Contraction; Deep Learning

INTRODUCTION

Sarcopenia is a skeletal muscle disorder characterized by the gradual loss of muscle mass and strength [1]. Initially perceived as an age-related condition primarily affecting the elderly, sarcopenia is now understood to be secondary sarcopenia, occurring independently of age and associated with various systemic illnesses [2]. It is significantly correlated with physical limitations and increased risk of mortality, underscoring the necessity for early and accurate diagnosis followed by appropriate treatment.

Diagnosis of sarcopenia involves assessing muscle mass, strength, and physical performance [1]. Despite proposals for new assessment items from various groups, there is a consensus on the importance of decreased strength and function as key components, although standardized criteria are lacking [3]. For instance, guidelines from the European Working Group on Sarcopenia in Older People (EWGSOP2) and the Asian Working Group for Sarcopenia (AWGS) recommend assessments such as grip strength and chair stands. Meanwhile, the Sarcopenia Definition and Outcomes Consortium and the International

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Conflict of Interest
The authors have no potential conflicts of interest to disclose.

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Working Group on Sarcopenia emphasize gait speed as a crucial indicator [1,2,4,5]. However, current tools for assessing muscle strength and function rely on volitional muscle function, posing challenges in accurately diagnosing sarcopenia in individuals with mobility impairments such as stroke. Particularly, those facing difficulties with sarcopenia assessment are at a higher risk of developing sarcopenia, highlighting the need for developing precise and convenient methods for diagnosing sarcopenia in this population [6].

Sarcopenia results in a reduction in the cross-sectional area of motor neuron myelin and in the mass of type II muscle fibers [7-9], leading to a decline in physical function [7,10]. Consequently, the analysis of motor units, comprising motor neurons and muscle fibers, is crucial for diagnosing sarcopenia. However, while conducting an invasive technique (such as needle electromyography [EMG] or biopsy) enables direct analysis of the condition of motor neurons and muscle fibers, this approach may not be appropriate from a health standpoint.

In our study, we focused on signals emitted during muscle contraction induced by electrical stimulation, termed stimulated muscle contraction signals (SMCSs). Surface EMG signals are recorded using a portable device during electrical stimulation of muscles. In addition, when electrical stimulation activates motor neurons and muscle fibers, response signals including M-waves, H-waves, and F-waves are generated from motor neurons and muscle fibers. SMCS encompasses these response signals from motor neurons and muscle fibers. Previous studies have shown that SMCS contains valuable information regarding muscle strength and endurance, demonstrating its potential as a promising digital biomarker for assessing muscle status [11]. Also, since sarcopenia negatively impacts muscle health by affecting motor neurons and muscle fibers, SMCS can be utilized to evaluate the degeneration of motor neurons and muscle fibers for sarcopenia diagnosis.

The aim of this study was to investigate the potential for diagnosing sarcopenia using SMCS measurements with a portable device in patients with mobility impairments such as hemiplegic stroke.

MATERIALS AND METHODS

Participants

The study included 40 stroke patients who were undergoing rehabilitation at Rhin Hospital, specialized in acute and subacute stroke rehabilitation. To be included, participants had to meet the following criteria: they must have experienced their first-ever stroke within the past 2 years, be above 18 years old, have had a hemiplegic stroke, and have provided written informed consent. Exclusion criteria consisted of the presence of neuromuscular diseases such as Parkinson's disease, Guillain-Barre syndrome, Myasthenia Gravis, or myopathy, unstable medical conditions, and severe cognitive impairment that would hinder compliance with the study. Ethical approval was obtained from the Korea National Institute for Bioethics Policy, and written informed consent was collected from each participant before their inclusion in the study (IRB number: 202210-01-032).

Data collection

The data were collected from 40 hemiplegic stroke patients using the wearable device exoPill (EXOSYSTEMS, Seongnam, Korea), which had been approved by the Korea Food and Drug Administration as a medical device. Muscles were electrically stimulated, and the SMCS were

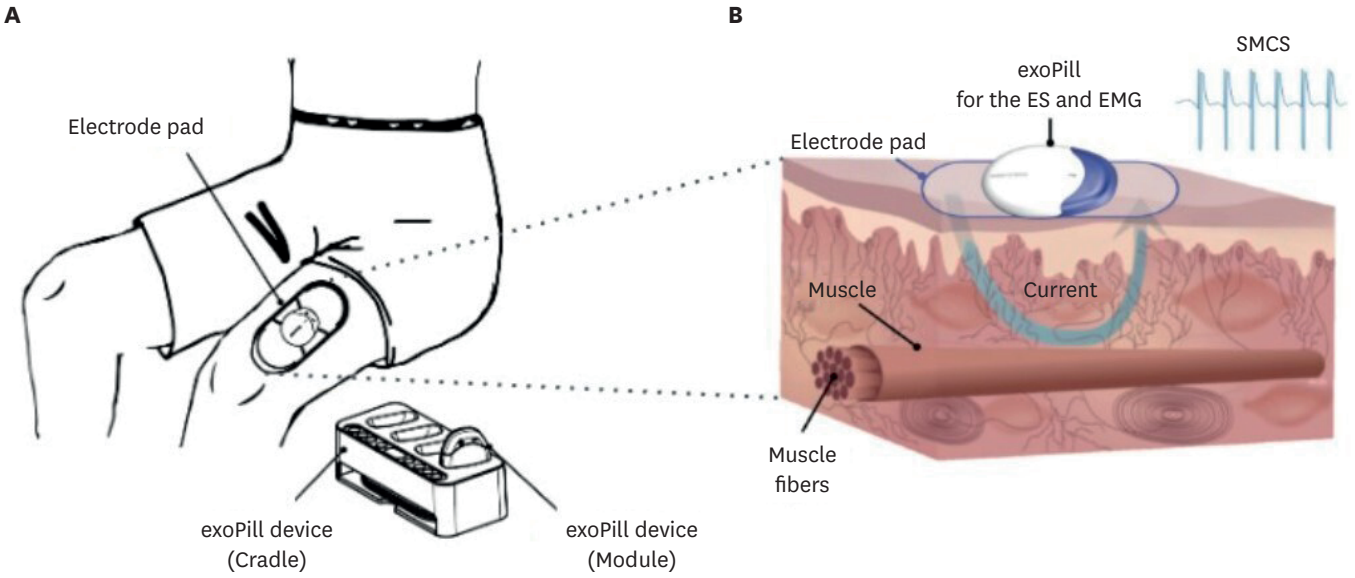

Fig. 1. Overview of SMCS measurement. (A) Example scene of SMCS measurement using the exoPill device. (B) Principle of SMCS acquisition.
SMCS, stimulated muscle contraction signal; ES, electrical stimulation; EMG, electromyography.

simultaneously captured using EMG sensors. Electrical stimulation frequency ranged from 5 to 30 Hz in 5 Hz increments over an 8-second period, with a 2 seconds rest period between stimulation. Finally, SMCS were recorded as the response signal by stimulating motor neurons and muscle fibers using electrical stimulation (**Fig. 1**).

SMCS was evaluated on both sides of the anterior thigh and forearm while participants were seated in chairs. Each limb underwent 3 measurement trials. A 30 minutes interval separated each measurement session. Since the diagnosis of sarcopenia in hemiplegic patients is primarily conducted on the unaffected side, data measured from the unaffected quadriceps femoris were utilized for the diagnosis, utilizing the data from the final measurement.

Feature extraction and selection

SMCS data are transformed from the time domain to the time-frequency domain using Intrinsic Mode Functions (IMFs) [12]. As the order of the IMF increases, only low-frequency components remain. Therefore, we divided the SMCS data into low-frequency and high-frequency components using IMF, including the original signal. Subsequently, spectrograms were generated using the Fast Fourier Transform [13], with a window size set to half of the stimulus frequency period and an overlap size set to half of the window size. Features were then extracted from all bins on the y-axis corresponding to frequencies in the spectrogram to analyze the muscle contraction pattern across the entire frequency range. Finally, the extracted features, including total power and measures of signal variability such as root mean square of the successive differences, standard deviation (SD), sample entropy, permutation entropy, cardinality, SD1, and SD2, served as indicators to assess the variability among frequency components [14,15].

The features extracted from spectrogram-based SMCS undergo a feature selection process before being used as inputs to the model. Feature selection aims to select only significant features among the extracted ones. We employed the Whitney test [16], with significance determined at $p < 0.01$. To address the data imbalance issue caused by the smaller number of

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patients in the sarcopenia group compared to the non-sarcopenia group in both the male and female cohorts, we employed the synthetic minority oversampling technique [17] during the training phase.

Multilayer perceptron (MLP)

The diagnostic model structure is based on a MLP [18]. MLP is a neural network structure that consists of multiple layers of perceptron neurons stacked together. It includes one or more hidden layers between the input and output layers. We set the model parameters as follows: HiddenLayerSizes were (32, 10), Activation function was tanh, and IterationLimit was set to 1,000. Considering the differences in muscle characteristics between males and females and the variation in diagnostic criteria for sarcopenia between genders, we constructed separate diagnostic models for males and females. To avoid overfitting due to the small number of data sets, we employed leave-one-out cross-validation to mitigate its impact on accuracy.

Statistical analysis

We utilized an MLP model for sarcopenia classification. Therefore, diagnostic performance was evaluated using model accuracy, specificity, sensitivity, and F1 score. All measurements were reported as average values across all cross-validation.

RESULTS

The demographic characteristics of participants based on male and female groups are shown in **Table 1**. All patients were of Asian (Korean) ethnicity, with an average age of 62 ± 11 years, comprising 28 men and 12 women. Sarcopenia diagnosis criteria were based on the latest EWGSOP2 standards using patients' handgrip strength and skeletal muscle index (SMI). Impaired mobility resulting from stroke-related motor dysfunction or unstable gait precluded the measurement of gait speed, thus leading to the decision to utilize EWGSOP2 instead of AWGS. As a result, a total of 6 out of 28 males belonged to the sarcopenia group, while 4 out of 12 females had sarcopenia.

The t-test was conducted to compare the data presented in **Table 1**. Skeletal muscle mass and SMI variables showed significant differences according to sarcopenia status, observed in both male and female groups. Additionally, the χ^2 test was applied to assess the association between the independent variable sarcopenia status and the dependent variables stroke type and underlying disease, but no significant difference was found.

The purpose of the diagnostic model was to accurately classify the minority of sarcopenia patients as having sarcopenia. The MLP classification based on SMCS features yielded excellent sarcopenia diagnosis accuracy of over 90%. In males, the performance exhibited an accuracy of 93%, specificity of 95%, sensitivity of 83%, and F1 score of 83%. Conversely, in females, all metrics including accuracy, specificity, and sensitivity demonstrated a performance of 100%. The visualization of this classification's performance can be further examined in **Fig. 2**, which shows the confusion matrix of all participants. **Table 2** summarizes the results of the diagnostic model.

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Table 1. Demographic characteristics of participants

Variables	Male (n = 28)		p value	Female (n = 12)		p value
	Sarcopenia (n = 6)	Non-sarcopenia (n = 22)		Sarcopenia (n = 4)	Non-sarcopenia (n = 8)	
Age (yr)	67.3 ± 7.9	56.6 ± 8.7	0.015*	59.0 ± 7.6	73.6 ± 10.5	0.047*
Height (cm)	168.7 ± 5.8	171.3 ± 5.3	0.325	155.3 ± 2.9	158.9 ± 3.0	0.101
Weight (kg)	61.8 ± 5.9	73.8 ± 7.8	0.002*	52.8 ± 4.3	60.8 ± 9.4	0.171
BMI (kg/m^2)	21.6 ± 2.2	25.2 ± 2.4	0.003*	21.9 ± 2.5	24.0 ± 3.6	0.346
SMM (kg/m^2)	24.5 ± 1.6	30.1 ± 3.4	0.001*	17.9 ± 0.9	20.7 ± 2.1	0.035*
SMI (kg/m^2)	6.9 ± 0.3	8.0 ± 0.7	< 0.001*	5.3 ± 0.1	6.3 ± 0.6	0.022*
Handgrip strength (kgf)	18.8 ± 7.3	32.0 ± 7.3	0.001*	13.1 ± 4.8	16.2 ± 7.8	0.531
Duration of stroke (mon)	11.5 ± 5.5	9.2 ± 6.8	0.464	8.5 ± 6.2	6.1 ± 5.2	0.539
Stroke type						
Infarction	4 (66.7)	15 (68.2)	1.000	2 (50)	4 (50)	1.000
Hemorrhage	2 (33.3)	7 (31.8)	1.000	2 (50)	4 (50)	1.000
Affected side						
Right	3 (50)	12 (54.5)	1.000	1 (25)	2 (25)	1.000
Left	3 (50)	10 (45.5)	1.000	3 (75)	6 (75)	1.000
Underlying disease						
Diabetes mellitus	2 (33.3)	7 (31.8)	1.000	1 (25)	2 (25)	1.000
High blood pressure	4 (66.7)	14 (63.6)	1.000	2 (50)	8 (100)	0.171
Tuberculosis	0 (0)	1 (4.5)	1.000	0 (0)	0 (0)	1.000
Hepatitis	0 (0)	0 (0)	1.000	0 (0)	1 (12.5)	1.000

Values are presented as number (%). Baseline values are presented as mean ± standard error of the mean.
BMI, body mass index; SMM, skeletal muscle mass; SMI, skeletal muscle index.
*Statistical significance was defined as $p < 0.05$.

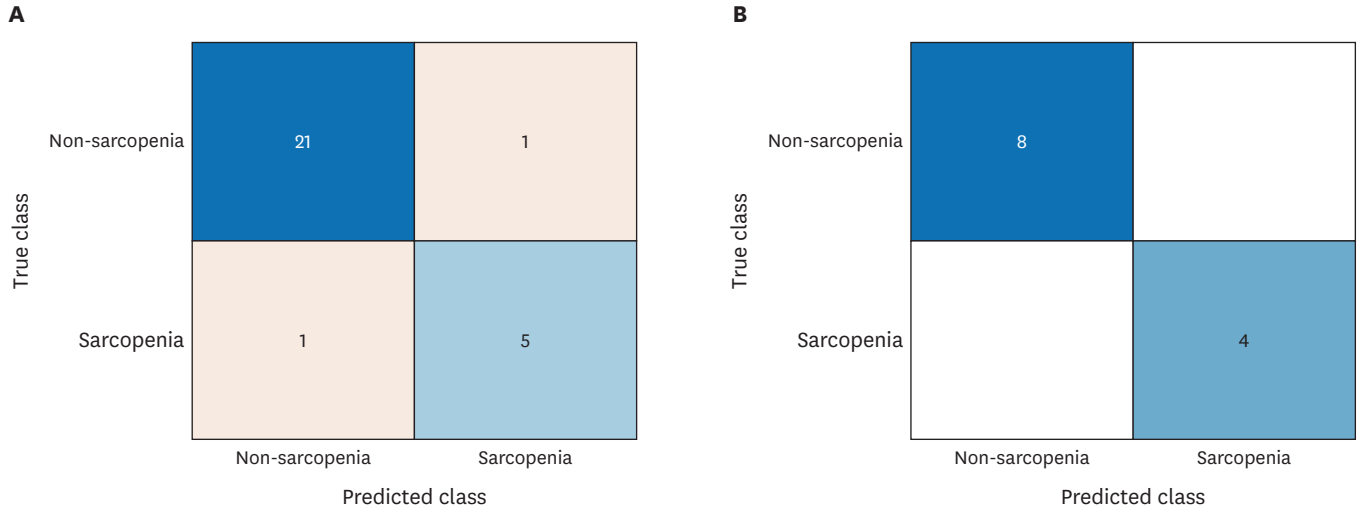

Fig. 2. Confusion matrix in stimulated muscle contraction signal sarcopenia diagnosis. (A) For 28 males, there were 2 misclassifications in sarcopenia diagnosis, resulting in an accuracy of 92.86%. (B) In the sarcopenia diagnosis of 12 females, the accuracy was 100%.

Table 2. Performance of the diagnosis model

Sex	Accuracy	Specificity	Sensitivity (Recall)	F1 score
Male (n = 28)	0.929	0.955	0.833	0.833
Female (n = 12)	1.000	1.000	1.000	1.000

DISCUSSION

The diagnosis of sarcopenia in stroke patients has relied on traditional methods such as handgrip strength and gait speed measurements. However, these methods have inherent limitations, such as the inability to accurately assess muscle function in individuals with severe impairment or those unable to cooperate fully with measurement procedures

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[6,19,20]. To address this challenge, this study developed a non-invasive method for sarcopenia diagnosis based on SMCS using a wearable device. Our proposed SMCS-based diagnosis approach achieved over 90% accuracy in detecting sarcopenia, suggesting its potential as a supplementary diagnostic tool. In particular, we validated the utility of the proposed method targeting stroke patients where precise muscle function measurement proves challenging.

In the result of feature selection, fewer features (8 features) were selected in the male group, implying a lesser number of meaningful features for diagnosing sarcopenia. On the other hand, for the female group, more features (35 features) were selected and used as model input, indicating that there were more significant features for classifying sarcopenia. It can be inferred that the diagnostic accuracy of female patients was higher. Therefore, future research could analyze the feature extraction and selection to deepen our results.

This study reports results based on 40 stroke patients; consequently, further validation with a larger cohort is required. Specifically, among the 40 patients, only 12 were female, with only 4 diagnosed with sarcopenia. Therefore, additional collection of more patients with sarcopenia is needed to validate the effectiveness of the proposed sarcopenia diagnosis approach.

The current study is based on the diagnostic criteria for sarcopenia according to EWGSOP2. However, considering the slight differences from AWGS criteria, it is anticipated that non-severe sarcopenia patients can be classified well. According to EWGSOP2, confirming the decline in muscle strength and mass is essential for diagnosing sarcopenia, while physical activity is necessary for diagnosing severe sarcopenia [1]. Stroke patients with limited mobility may encounter difficulties in conducting assessments for severe sarcopenia. Therefore, standardized criteria are necessary for such patient groups.

In conclusion, we experimentally demonstrated the feasibility of diagnosing sarcopenia using SMCS data obtained through the wearable device. This study revealed the potential to use this novel technique in the clinical setting, even in stroke patients with hemiplegia, reliably assessing muscle weakness. In summary, SMCS-based sarcopenia diagnosis presents a promising avenue for overcoming the limitations of traditional methods, offering a more accurate and comprehensive approach to diagnosing sarcopenia in stroke patients.

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