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Neuromuscular conditions in post-stroke ankle-foot dysfunction reflected by surface electromyography

Ying Xu[1,2], Juan Wang[2], Shujia Wang[2], Jinping Li[2], Ying Hou[2*] and Aisong Guo[1*]

Abstract

Background Rating scales and linear indices of surface electromyography (sEMG) cannot quantify all neuromuscular conditions associated with ankle-foot dysfunction in hemiplegic patients. This study aimed to reveal potential neuromuscular conditions of ankle-foot dysfunction in hemiplegic patients by nonlinear network indices of sEMG.

Methods Fourteen male patients with hemiplegia and 10 age- and sex-matched healthy male adults were recruited and tested in static standing position. The characteristics of the root mean square (RMS), median frequency (MF), and three nonlinear indices, the clustering coefficient (*C*), the average shortest path length (*L*), and the degree centrality (DC), of eight groups of muscles in bilateral calves were observed.

Results Compared to those of the control group, the RMS of the medial gastrocnemius (MG), flexor digitorum longus (FDL), and extensor digitorum longus (EDL) on the affected side were significantly lower ($P<0.05$), and the RMS of the tibial anterior (TA) and EDL on the unaffected side were significantly higher ($P<0.05$). The MF of the EDL on the affected side was significantly higher than that on the control side ($P<0.05$). The *C* of the unaffected side was significantly higher than that of the control group, whereas the *L* was lower ($P<0.05$). Compared to those of the control group, the DC of the TA, EDL, and soleus (SOL) on the unaffected sides were higher ($P<0.05$), and the DC of the MG on the affected sides was lower ($P<0.05$).

Conclusion The change trends and clinical significance of these three network indices, including *C*, *L*, and DC, are not in line with those of the traditional linear indices, the RMS and the MF. The *C* and *L* may reflect the degree of synchronous activation of muscles during a certain motor task. The DC might be able to quantitatively assess the degree of muscle involvement and reflect the degree of involvement of a single muscle. Linear and nonlinear indices may reveal more neuromuscular conditions in hemiplegic ankle-foot dysfunction from different aspects.

Trial registration ChiCTR2100055090.

Keywords Stroke, Lower extremity, Neuromuscular manifestations, Electromyography

*Correspondence:
Ying Hou
yinghou@njmu.edu.cn
Aisong Guo
guoasg@ntu.edu.cn

[1]Department of Rehabilitation Medicine, Affiliated Hospital of Nantong University, Medical School of Nantong University, Nantong 226001, China
[2]Department of Rehabilitation Medicine, Suzhou Municipal Hospital, The Affiliated Suzhou Hospital of Nanjing Medical University, Gusu School of Nanjing Medical University, Suzhou 215000, China

Background

Ankle-foot dysfunctions not only restrict the activities of daily living of patients with post-stroke but also cause common and serious secondary injuries, such as falls, cranial injury, fractures, joint damage, and even death [1, 2]. Ankle-foot dysfunction is an important key point in post-stroke patients with hemiplegia.

The essential neuromuscular pathological conditions resulting in poor muscle coordination in post-stroke patients with hemiplegia are muscle weakness, hypotonia, spasticity, rigidity, and spasm [3, 4]. Accurate treatments, such as botulinum injection, are based on the quantification of neuromuscular conditions in muscles [5, 6].

However, currently, the physical examination and rating scales commonly used in clinical practice are not able to reflect the neuromuscular status of muscles but can assess the comprehensive functions of hemiplegic patients [7]. Even surface electromyography (sEMG), which can accurately and objectively detect and analyse the electrophysiological signals generated by muscles during various motor activities [8, 9], still fails to identify different neuromuscular conditions to date because traditional algorithms, such as linear analysis, nonnegative matrix factorization (NMF), and co-contraction index (CCI), cannot reflect synergistic interactions among muscles [10, 11]. Currently, some of the nonlinear indices of electromyography have high sensitivity and reliability for analysing real-time changes in intermuscular synchronicity and have been applied for tracking the topologies of muscle networks and sensorimotor integration in poststroke patients and hand grabbing clinical studies [12, 13]. Our team applied the clustering coefficient (C), the average shortest path length (L), and the degree centrality (DC) based on multiplex recurrence network (MRN) and weighted network (WN) to study the forearm muscles, gluteal muscles and thigh muscles in healthy participants, and the results showed that these nonlinear indices can be used to analyse intermuscular coordination [10, 13].

Table 1 Demographic data of the two groups

Variable	Patient group ($n=14$)	Control group ($n=10$)	P values
Age, year	47.14 ± 15.94	54.00 ± 8.21	0.103
Height, cm	171.14 ± 4.02	167.90 ± 5.28	0.564
Weight, kg	70.43 ± 10.75	68.30 ± 8.21	0.298
Sex, male/female	14/0	10/0	1.000
Stroke subtype, hemorrhagic/ischemic	2/12	--	--
Side of hemiplegia, right/left	7/7	--	--
Duration between the onset and enrollment, month	8.18 ± 3.41	--	--

In this study, we used the C, L and DC to analyse electrophysiological signals of muscles of the lower limbs to reveal different neuromuscular conditions associated with ankle-foot dysfunctions in poststroke patients with hemiplegia and to propose accurate muscle evaluation methods for clinical decisions. In this study, it was hypothesized that nonlinear indices could identify differences in the synergistic movement of the calf muscles between hemiplegic patients and the control group.

Methods

The study protocol was approved by the Ethics Committee of Suzhou Municipal Hospital (study registration number: ChiCTR2100055090). This study was conducted in a motor control laboratory of a general hospital in accordance with the Declaration of Helsinki. This study conforms to all Strengthening the Reporting of Observational Studies in Epidemiology guidelines and reports the required information accordingly.

Participants

This was an exploratory preliminary study. To reduce the potential effect of sex on muscle thickness and electrical signals [14], fourteen male typical hemiplegia patients hospitalized in the Department of Rehabilitation Medicine who met the nadir criteria were selected, and 10 sex- and age-matched healthy controls were recruited (control group). All subjects were informed about the details of the trial, and written informed consent was obtained from all participants before trial enrollment. The general data of the participants are detailed in Table 1. The inclusion criteria for hemiplegic patients were as follows: (1) confirmed diagnosis of cerebral infarction or cerebral hemorrhage by cranial CT or MRI; (2) first stroke; (3) lower limb function in Brunnstrom stage III; (4) no cognitive impairment, with a Mini-Mental State Examination (MMSE) [15] score of ≥24 and ability to cooperate to complete the experiment; and (5) ability to stand independently for more than 10 min. The exclusion criteria for hemiplegic patients were (1) a history of diseases or injuries to the nerve, muscle, or skeletal system of the lower limbs; (2) severe lumbar and cervical spine diseases; (3) pain in the lower limbs; (4) dizziness or vestibular system diseases; (5) recent use of drugs that affect balance; and (6) severe visual impairment. The inclusion criteria for the control group were as follows: (1) age, height, and handedness matched with the patient group; (2) normal symmetrical standing posture; (3) no significant difference in the shape of the right and left calves according to visual observation. The exclusion criteria for the control group were (1) history of musculoskeletal and osteoarthritic injuries of the lower limb (2) increased tendon reflexes on the Achilles tendon pulling test.

Experimental procedures

Before the test, the subjects were familiarized with the test environment and procedures under the guidance of the testers. Sixteen muscles were selected from the subject's left and right sides: the tibial anterior (TA), extensor digitorum longus (EDL), peroneal longus (PL), peroneus brevis (PB), soleus (SOL), medial gastrocnemius (MG), lateral gastrocnemius (LG), and flexor digitorum longus (FDL). A 16-channel wireless sEMG system (Trigno™, Delsys, USA) was utilized to record the physiological electrical signals of the muscles, and the sampling frequency was set at 2000 Hz. Before the test, the skin at the relevant electrode attachment sites was shaved, polished with scrubbing cream, and cleaned with alcohol. The sEMG electrodes were affixed to the relevant attachment sites of the six groups of muscles, except the EDL and FDL, bilaterally along the muscle fibres according to the recommendations of the European Union on sEMG signal electrode affixing [16]. Musculoskeletal ultrasound (X-Porte TTC) was used to visualize the EDL and FDL. The EDL was located on the middle of the tibia, 0.5 cm inwards from the lateral recess of the lower leg when the foot was turned over. The FDL was located 0.5 cm medial to the medial border of the tibia at the junction of the middle and lower 1/3 of the calf.

During the formal test, the subjects stood in the natural position with their hands hanging down, their eyes looking straight in front, and they listened to the testers' orders to stand still for 30 s to complete the static standing test. The test was repeated three times, with a five-minute sitting break between each test.

Data analyses

In this study, traditional linear time- and frequency-domain indices of each channel sEMG time series, root mean square (RMS) and median frequency (MF), nonlinear dynamical network indices of multichannel sEMG time series, the *C*, *L*, and DC were analysed. The RMS can reflect the number and degree of motor unit activations during muscle activity under neural control. The MF can reflect the proportion and state of muscle fibres in muscle tissue to a certain extent and is also an important indicator of muscle fatigue in clinical practice [9]. The *C* is used to describe the extent to which neighboring nodes in a network aggregate to form clusters, and the *L* is the average of the shortest paths between all node pairs. In this study, *C* and *L* were used *to* measure the dynamic closeness of the physiological electrical activity of multiple muscles. The larger the *C* is and the smaller the *L* is, the greater the degree of coordination among muscles [17, 18]. The DC represents the centrality of nodes in a network. In this study, we applied DC to observe changes in the dynamic structure of a single muscle at the global level, and a larger DC of a muscle was associated with greater involvement and contribution to multimuscle coordination [19].

MATLAB R2020a (MathWorks, Natick, MA, USA) was used to preprocess the sEMG signals and extract the indices. To mitigate interference arising from signal instability at the initiation and termination of each trial, a 15-second intermediate signal segment was selected for subsequent analyses. A fourth-order Butterworth bandpass filter with a frequency range of 20 to 500 Hz was utilized to filter the sEMG signals. A sliding window approach, consisting of 1000 sample points with an overlap of 250 sample points, was applied to extract the assessment indices. The average of the assessment indices obtained from all windows was considered the result of a single trial. The average of the results of the three trials was taken for statistical analyses.

RMS refers to the square root of the amplitude of the physiological electrical signal of the muscle over a certain period. The calculation formula of the RMS is as follows:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} u(i)^2}{N}} \tag{1}$$

where u is a one-channel sEMG time series of length N

MF is the intermediate value of muscle fibre firing frequency during skeletal muscle contraction. The MF is defined as:

$$\int_{f_s}^{f_{MF}} P(f)df = \int_{f_{MF}}^{f_e} P(f)df = \frac{1}{2}\int_{f_s}^{f_e} P(f)df \tag{2}$$

where $P(f)$ is the power spectrum and f_s and f_e are the start and end frequencies of the power spectrum, respectively.

The *C*, *L*, and DC were extracted from the nonlinear dynamical WN. First, each channel sEMG time series u could be reconstructed as a trajectory in high-dimensional phase space according to Taken's time delay theory [20, 21]. A high-dimensional vector of the trajectory can be constructed by the following formula:

$$v_i = \left[u_i, u_{i+\tau}, \ldots, u_{i+(d-1)\tau}\right] \tag{3}$$

where $i = 1, 2, \ldots, N - (d-1)\tau$ and N is the length of the sEMG time series. The time delay τ was set to 5 samples, and the embedding dimension d was set to 4 according to the mutual information and false nearest neighbors [22–24]. Then, the recurrence network (RN) of the single-channel sEMG time series could be generated by comparing the distance between the state points of the reconstructed trajectory and a predefined threshold value according to the following formula [25]:

$$RN_{i,j} = \Theta\left(\varepsilon - \|v_i - v_j\|\right) - \delta \quad (4)$$

where v is the reconstructed phase space trajectory, $i,j = 1,\ldots,N$, $\|\cdot\|$ is the Euclidean distance, ε is the threshold value, Θ is the Heaviside function, and δ is the Kronecker delta symbol. In cases where the distance between two state points was less than or equal to the threshold, a connection existed between the corresponding nodes of the RN. Conversely, if the distance exceeded the threshold, there was no connection between the corresponding nodes. The threshold was established at 80% of the maximum phase space radius based on our prior research [26]. The construction of the RN was facilitated using the cross-recurrence plot toolbox 5.1 of MATLAB. As a two-dimensional connectivity matrix, the similarity of the node degree distribution of the RN between two muscles can be measured by mutual information (*I*), whose calculation formula is as follows:

$$I_{\alpha,\beta} = \sum_{k^{[\alpha]}}\sum_{k^{[\beta]}} P\left(k^{[\alpha]},k^{[\beta]}\right)\log\frac{P\left(k^{[\alpha]},k^{[\beta]}\right)}{P\left(k^{[\alpha]}\right)P\left(k^{[\beta]}\right)} \quad (5)$$

where $P\left(k^{[\alpha]}\right)$ and $P\left(k^{[\beta]}\right)$ are the degree distribution probabilities of RN α and β, respectively. The $P\left(k^{[\alpha]},k^{[\beta]}\right)$ is the joint degree distribution probability of the existence of nodes with degree $k^{[\alpha]}$ in RN α and $k^{[\beta]}$ in RN β. Considering each RN as a node, the *I* of the RN between two muscles is used as the weight of the connecting edge, and the WN is established (Fig. 1).

The structural characteristics of the WN can be quantitatively described by related parameters, including *C* and *L*. The *C* is given by [25]:

$$C = \frac{1}{m}\sum_{\alpha}\frac{1}{k_\alpha\left(k_\alpha - 1\right)}\sum_{\beta}\sum_{\gamma}\left(I_{\alpha,\beta}I_{\beta,\gamma}I_{\alpha,\gamma}\right)^{\frac{1}{3}} \quad (6)$$

where k_α is the degree of node α and *m* is the number of muscles and channels of the sEMG time series. The *L* is calculated as follows [25]:

$$L = \sum_{\alpha,\beta\in V}\frac{d\left(\alpha,\beta\right)}{m\left(m-1\right)} \quad (7)$$

where *V* is the set of all nodes of WN and $d\left(\alpha,\beta\right)$ is the weighted shortest path length between nodes α and β.

The DC of the α^{th} node in the WN is defined as follows [27]:

$$DC_\alpha = \sum_{\beta\in V} I_{\alpha\beta} \quad (8)$$

The RMS and MF were extracted from the bilateral muscles. In the patient group, the RMS and MF values for the affected and unaffected side were evaluated separately. In the control group, the RMS and MF of the bilateral same muscles were averaged as the result for that muscle. The WN of the left lower limb and of the right lower limb were constructed. In the patient group, the *C*, *L*, and DC were constructed for the affected and unaffected sides, respectively. In the control group, the *C*, *L*, and DC of the left and right lower limbs were averaged as the WN indices of a single lower limb.

Statistical analyses

The data were analysed using the statistical package SPSS version 26.0 (IBM Corp, Armonk, NY). Variables are

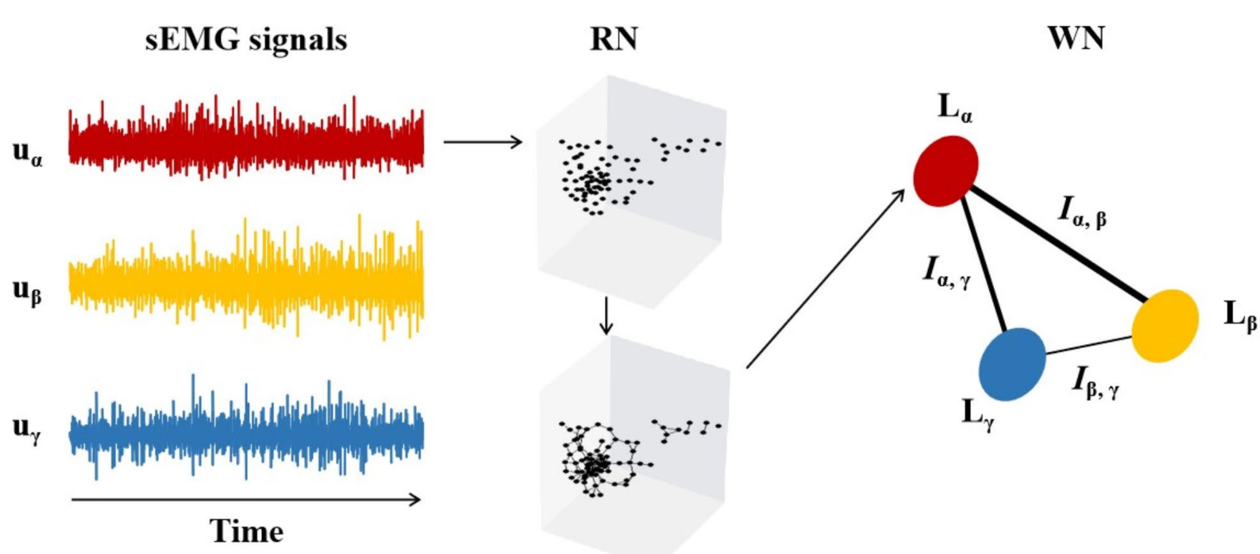

Fig. 1 Schematic of the WN construction

expressed as the mean ± standard deviation (SD). Shapiro–Wilk's method was used for normality testing. The RMS data did not conform to a normal distribution, and the rank sum test was used for comparisons between two groups. The MF, *C*, *L* and DC data were normally distributed, and a t test was used for comparisons between groups. Paired t tests were used to compare the affected and unaffected sides, and independent sample t tests were used to compare the affected side with the control group and the unaffected side with the control group. Differences were considered statistically significant at $P < 0.05$. The Confidence Interval (CI) was an estimate of the total population mean for the index that was based on the data obtained in the sample for this study. A 95% CI indicates that there is a 95% chance that the interval includes the true mean for the total population.

Results

In this study, the data of participants in the two groups were collected without dropout or missing data.

The RMS

The RMS of the MG, FDL, and EDL on the affected side were significantly lower than those of the control group ($P < 0.05$). The RMS of the TA and EDL on the unaffected side were higher than those of the control group ($P < 0.05$). Compared with those on the unaffected side, the RMS of the TA, EDL, MG, SOL and PL on the affected side were significantly lower ($P < 0.05$). There were no significant differences in the other muscles between the two groups. ($P > 0.05$) (Table 2).

Table 2 Comparison of the RMS and MF between any two groups

Variable	Affected side		Control group		Unaffected side	
	mean ± SD	95%CI	mean ± SD	95%CI	mean ± SD	95%CI
Tibial Anterior						
RMS(μV)	3.70 ± 1.49[c]	(2.84–4.57)	3.72 ± 3.06	(1.54–5.92)	11.93 ± 11.37[b]	(5.36–18.49)
MF (Hz)	119.82 ± 25.99	(104.82-134.83)	139.09 ± 16.32	(127.42-150.77)	136.35 ± 25.29	(121.75-150.95)
Extensor Digitorum Longus						
RMS(μV)	5.07 ± 3.54[ac]	(3.02–7.11)	6.81 ± 2.39	(5.10–8.52)	20.52 ± 22.19[b]	(7.71–33.33)
MF (Hz)	125.34 ± 30.79[ac]	(107.56-143.12)	96.47 ± 28.92	(75.77-117.15)	94.94 ± 37.38	(73.35-116.52)
Lateral Gastrocnemius						
RMS(μV)	4.69 ± 3.31	(2.77–6.60)	5.25 ± 2.29	(3.61–6.89)	7.74 ± 6.85	(3.79–11.70)
MF (Hz)	135.46 ± 19.58	(124.15-146.76)	146.22 ± 17.67	(133.58-158.85)	131.74 ± 23.82	(117.98-145.48)
Medial Gastrocnemius						
RMS(μV)	4.71 ± 2.81[ac]	(3.10–6.34)	13.93 ± 6.90	(8.99–18.86)	16.56 ± 12.87	(9.13–23.99)
MF (Hz)	131.11 ± 26.83	(115.62–146.60)	147.38 ± 19.99	(133.08-161.58)	144.71 ± 21.30	(132.42-157.01)
Flexor Digitorum Longus						
RMS(μV)	7.00 ± 4.47[a]	(4.42–9.59)	11.75 ± 4.63	(8.44–15.06)	11.13 ± 7.59	(6.75–15.51)
MF (Hz)	138.03 ± 22.73	(124.90-151.16)	152.34 ± 21.29	(137.72-167.57)	140.78 ± 19.85	(129.32-152.24)
Soleus						
RMS(μV)	6.64 ± 3.60[c]	(4.56–8.72)	10.60 ± 7.20	(5.46–15.75)	15.69 ± 9.59	(10.15–21.23)
MF (Hz)	141.48 ± + 25.77[c]	(126.60-156.36)	138.92 ± 33.11	(115.24–162.60)	161.17 ± 30.04	(143.83-178.51)
Peroneal Longus						
RMS(μV)	6.11 ± 4.26[c]	(3.66–8.57)	6.00 ± 3.07	(3.80–8.19)	10.59 ± 7.38	(6.33–14.86)
MF (Hz)	127.22 ± 24.48	(113.09-141.36)	141.78 ± 23.97	(124.64-158.93)	141.24 ± 23.83	(127.48–155.00)
Peroneus Brevis						
RMS(μV)	9.08 ± 8.92	(3.91–14.23)	8.74 ± 4.10	(5.80-11.67)	13.67 ± 15.01	(5.00-22.34)
MF (Hz)	151.19 ± 26.22	(136.05-166.33)	139.35 ± 18.05	(126.44-152.26)	140.33 ± 31.08	(122.38-158.27)

[a]Significant difference between the affected side and the control group.

[b]Significant difference between the unaffected side and the control group.

[C]Significant difference between the affected side and the unaffected side.

Table 3 Comparison of the *C* and *L* between any two groups

Variable	Affected side		Control group		Unaffected side	
	mean ± SD	95%CI	mean ± SD	95%CI	mean ± SD	95%CI
C	0.75 ± 0.04[c]	(0.72–0.77)	0.74 ± 0.03	(0.72–0.77)	0.79 ± 0.05[b]	(0.76–0.82)
L	2.51 ± 0.64[c]	(2.14–2.88)	2.17 ± 0.21	(2.02–2.32)	1.83 ± 0.19[b]	(1.72–1.94)

[a]Significant difference between the affected side and the control group.

[b]Significant difference between the unaffected side and the control group.

[c]Significant difference between the affected side and the unaffected side.

Table 4 Comparison of the DC between any two groups

Muscles	Affected side		Control group		Unaffected side	
	mean ± SD	95%CI	mean ± SD	95%CI	mean ± SD	95%CI
Tibial Anterior	6.64 ± 1.33[c]	(5.87–7.41)	6.31 ± 1.02	(5.58–7.03)	7.65 ± 1.59[b]	(6.73–8.57)
Extensor Digitorum Longus	6.89 ± 1.36[c]	(6.11–7.68)	6.83 ± 0.87	(6.21–7.45)	8.06 ± 1.22[b]	(7.36–8.77)
Lateral Gastrocnemius	6.83 ± 1.29[c]	(6.08–7.57)	7.09 ± 0.82	(6.50–7.67)	7.81 ± 1.04	(7.21–8.42)
Medial Gastrocnemius	6.70 ± 1.31[ac]	(5.95–7.45)	8.00 ± 0.89	(7.36–8.64)	8.41 ± 0.91	(7.88–8.94)
Flexor Digitorum Longus	7.26 ± 1.65[c]	(6.31–8.22)	7.87 ± 0.90	(7.23–8.51)	8.15 ± 0.76	(7.71–8.59)
Soleus	7.40 ± 1.53[c]	(6.51–8.28)	7.26 ± 0.76	(6.72–7.80)	8.09 ± 0.85[b]	(7.60–8.59)
Peroneal Longus	7.38 ± 1.35	(6.60–8.16)	7.30 ± 0.81	(6.72–7.88)	7.77 ± 1.16	(7.10–8.44)
Peroneus Brevis	7.31 ± 1.71	(6.32–8.29)	7.10 ± 0.94	(6.43–7.77)	7.76 ± 1.08	(7.13–8.38)

[a]Significant difference between the affected side and the control group.

[b]Significant difference between the unaffected side and the control group.

[c]Significant difference between the affected side and the unaffected side.

The MF

The MF of the EDL on the affected side was significantly higher than that of the control group ($P<0.05$), whereas the differences in the remaining muscles were not significant between the affected side and the control group or between the unaffected side and the control group ($P>0.05$). Compared with that on the unaffected side, the MF of the EDL on the affected side significantly increased, whereas the MF of the SOL significantly decreased ($P<0.05$). (see Table 2).

The *C* and *L*

When the two groups were compared, the C of the unaffected side was significantly higher than that of the control group, whereas the L was lower ($P<0.05$). The C was significantly lower and L was significantly higher on the affected side than on the unaffected side ($P<0.05$). There were no differences in the C and L between the affected side and control group ($P>0.05$).(see Table 3).

The DC

Compared to those in the control group, the DC of the MG on the affected side was lower ($P<0.05$), and the DC of the TA, EDL, and SOL on the unaffected side was higher ($P<0.05$). The DC of the TA, EDL, MG, LG, FDL, and SOL were significantly lower on the affected side than on the unaffected side ($P<0.05$). No differences were observed in the other muscles (see Table 4).

Discussion

This study was the first to apply these nonlinear indices, which can reflect the synchronous relationship between muscles, and the calf muscles of hemiplegic patients. In this study, we observed linear and nonlinear electrophysiological indices of calf muscles in hemiplegic patients and healthy adults. We enrolled patients in Brunnstrom stage III to standardize the neuromuscular conditions of the calf muscles.

The results of the comparison between the affected sides and the unaffected sides showed that the conditions of the neural control of the calf muscles in hemiplegic patients were that the muscle activation and coordination increased morae on the unaffected sides than the control group. In contrast, the muscle activation was reduced on the affected side and the synergistic involvement of the MG was significantly lower. The overall coordination of the eight muscles on the affected side, with values similar to those of the control group, should not be considered normal and further evaluation of the partial network was needed. The findings of this study revealed that nonlinear indices could identify changes in muscle coordination in the bilateral calf in patients with hemiplegia, and their change trends differed from those of the linear indices.

The RMS

The RMS of the MG, FDL and EDL on the affected side decreased, while the RMS of the TA and EDL on the unaffected side increased compared to those in the control group. This suggested that muscle activation of the

MG, FDL and EDL on the affected side decreased, while activation of the TA and EDL on the unaffected side increased during static standing. The results are consistent with previous clinical studies. The MG on the affected side was prone to atrophy and muscle activation was significantly reduced [28, 29]. Patients with hemiplegia often experience foot drop and toe gouging, so the FDL is shortened for a long period of time, resulting in decreased size and poorer active activation. The RMS of the EDL on the affected side was reduced, while the RMS of the TA did not differ from that of the control group [30, 31]. In addition, the RMS of the TA and EDL on the unaffected side were higher. This may be because the muscles on the unaffected side need to be over-activated to maintain balance [32]. This finding indicated that the RMS could identify significant weakness of paralyzed muscles and voluntary conditions of unaffected muscles.

The MF

The results of this study showed that the MF of the EDL on the affected side in hemiplegic patients was higher than that of the control group during static standing, and there was no significant difference in the MF between the unaffected side and the control group. No studies have reported differences in the MF of muscles on the affected side between hemiplegic patients and healthy individuals. MF represents the median muscle fibre discharge frequency during skeletal muscle contraction. Generally, MF is influenced by the composition ratio of type I and type II fibres. Type II fibres typically exhibit high-frequency discharge, while type I fibres exhibit low-frequency electrical activity [33, 34]. Clinical studies have demonstrated that the MF decreases following muscle fatigue and centrifugal contraction, which is primarily associated with an increase in the proportion of type I fibres and a reduction in the muscle discharge rate [35, 36]. We hypothesize that the notably increased MF in the affected EDL may be linked to hyperresponsiveness and loss of postsynaptic inhibition induced by the shortened antagonistic muscle FDL [37, 38].

The C and L

The results showed an increase in the C and a decrease in the L on the unaffected side compared to those of the control group, but there were not significantly different from those in the affected group. C and L measure the closeness of the kinetic association of muscle electrical activity. The larger C is and the smaller L is, the tighter the connection of the nodes and the more efficient the information transfer. The results of this study showed that there was an increase in calf muscle coordination on the unaffected side, whereas there was no significant difference between the affected side and the control group. To maintain the balance of the trunk, muscles of the lower limb on the unaffected side with more weight-bearing need to be activated more, and at this time, multimuscle coordination is increased on the unaffected side. The activation and synergistic state on the unaffected side was different from that of the control group, which may be due to compensatory changes on the unaffected side [39]. This study suggested that it may be inappropriate to use the unaffected side as a control group when investigating motor dysfunction of the affected muscles in hemiplegic patients in static standing, when the muscle synergistic state of the unaffected side has already been altered, which is consistent with the findings of a previous study [40]. However, the C and L on the affected side did not differ from that of the control group, as the C and L in this study reflected the average degree of the overall connection of all the eight muscles, including partial connections with potentially varying synchronization. Patients with hemiplegia have many neuromuscular conditions in the lower limb, such as spasticity with tight association and hypotonia with decreased efficiency of information transfer. Therefore, in this study, although the C and L on the affected side were not significantly different from those of the control group, this did not mean that any local part within the network was normal. The results showed a decrease in the C and an increase in the L on the affected side compared to those of the unaffected side, suggesting an asymmetry in the coordination condition of the bilateral calves in hemiplegic patients. This study suggested that it may be inappropriate to use the unaffected side as a control group when investigating motor dysfunction of the affected muscles in hemiplegic patients in static standing, when the muscle synergistic state of the unaffected side has already been altered, which is consistent with the findings of a previous study [40].

The DC

This is the first time that the DC has been used to assess muscles in patients with hemiplegia. Compared to those of the control group, the DC of the MG on the affected side was lower, while the DC of the TA, EDL, and SOL on the unaffected side were higher. This finding is consistent with previous studies in which the MG on the affected side exhibited significant atrophy, accompanied by a notable decrease in muscle motor function, and the extensor muscles on the unaffected side displayed a voluntary compensatory state. Compared with the unaffected side, the DC of the six muscles on the affected side were significantly lower except for the PL and PB. It reflected the asymmetric synergistic involvement of bilateral calf muscles in hemiplegic patients. This finding implies that the DC could represent the degree of voluntary involvement of muscles, similar to its role in brain connective activation analysis [41, 42].

In this study, it was found that the changes of the values of the DC were not in line with those of the RMS. For example, when compared with the control group, the RMS of the FDL and EDL on the affected side was decreased, unaccompanied by the reduction in the DC; and the DC of the SOL on the unaffected side increased, but the RMS of it did not exhibit a significant change. The different results of the two indices may be explained by their different clinical significance: the RMS reflects the amount and degree of motor unit activation during voluntary and unvoluntary muscle activity; in contrast, the DC reflects the degree of voluntary involvement of certain muscles based on overall muscle coordination analysis. It is possible that the DC may reflect the degree of voluntary neural control during a motor task. Further research may focus on its specific significance in clinical practice.

Study limitations

This study has several limitations. The sample size of this study was relatively small, and only patients with Brunnstrom stage III disease of the lower extremity were included. Myoelectric analysis was not performed in this study in conjunction with other sEMG indices in hemiplegic patients with movement patterns. Further studies can use linear indices, such as integrated electromyography (IEMG), average electromyography (AEMG) and mean power frequency (MFP), as well as nonlinear indices, such as interlayer mutual information (I) and average edge overlap (ω), for analysis. The similarities and differences of the values of these indices may distinguish more characteristics of neural control of muscles.

Conclusions

In this study, we observed the characteristics of linear and nonlinear electrophysiological indices of calf muscles in hemiplegic patients and healthy adults. The change rules and clinical significance of the C, L, and the DC are not in line with the traditional linear indices, the RMS and MF. The RMS and MF can assess the degree of muscle activation in terms of the overall activation function of the muscle group and the degree of intramuscular fibre recruitment, respectively. The C and L may reflect degrees of synchronous activation of muscles during a certain motor task. The DC might be able to quantificationally assess voluntary involvement degrees of muscles. This study showed that muscles with decreased RMS may not have a significant change in DC, and similarly, muscles with no significant change in RMS may have an increased DC. The DC may reflect the synchronous response of muscles to neural control, but the RMS reflects the degree of muscle activation when the muscle acts as an effector of neural control. Employing a combination of linear and nonlinear indices facilitates the identification of more neuromuscular conditions in hemiplegic ankle-foot dysfunction. This was a prospective observational study, further studies can apply these indices to the analysis of upper limb muscle coordination.

Abbreviations

sEMG	Surface electromyography
RMS	Root mean square
MF	Median frequency
C	Clustering coefficient
CCI	Agonist-antagonist cocontraction
L	Average shortest path length
DC	Degree centrality
TA	Tibial Anterior
EDL	Extensor digitorum longus
LG	Lateral gastrocnemius
MG	Medial gastrocnemius
FDL	Flexor digitorum longus
SOL	Soleus
PL	Peroneal longus
PB	Peroneus brevis
NMF	Nonnegative matrix factorization
MMSE	Mini-Mental State Examination
MRN	Multiplex recurrence network
WN	Weighted network

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Author contributions

AG and YH conceived the conception and design of the study. JL and JW performed the experiment. JL, YX and SW analyzed the data. YX drafting the article. All authors reviewed and approved the final manuscript.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The experimental procedures were approved by the Ethics Committee of Suzhou Municipal Hospital (K-2022-161-K01) and were in accordance with the Declaration of Helsinki. All participants provided informed consent before the test.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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