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Research article

Cross-correlated fractal components of H-wave amplitude fluctuations in medial gastrocnemius and soleus muscles

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ABSTRACT

The time series of the H-wave amplitude in soleus muscle (SOL) shows fractal (long-range) correlation, which is attributed to input from supraspinal centers. However, whether such long-range power-law correlated input also contributes to the synergistic muscles remains unclear. The purpose of this study was therefore to examine the correlation in the fractal components of H-wave amplitude fluctuations between the synergistic muscles used for plantar flexion, i.e., the medial head of the gastrocnemius muscle (MG) and SOL. In eight young male participants, consecutive H-reflexes were recorded almost simultaneously from the MG and SOL at a stimulation frequency of 0.5 Hz for 30 min. We performed detrending moving-average cross-correlation analysis (DMCA) for each of the H- and M-wave amplitude time series between MG and SOL to assess the existence of a common noise input contributing to these long-range correlations. The cross-correlation coefficient ρDMCA (-1 to 1) was calculated to quantify the strength of the correlation between two different time series. The results indicated a significant long-range power-law correlation between H-wave amplitudes in MG and SOL (ρDMCA: 0.50 (0.22) and 0.22 (0.17), mean (standard deviation) for the original and randomly shuffled surrogate data, respectively, $P < 0.05$). This was not the case for M-wave amplitudes (ρDMCA: 0.29 (0.23) and 0.20 (0.15), $P > 0.05$). We conclude that there is a common noise input governing these synergistic muscles, possibly due to supraspinal origin, causing long-range power-law correlations in monosynaptic reflexes.

1. Introduction

The amplitude of the monosynaptic reflex fluctuates considerably with time [1–4]. Some previous studies using static analyses have reported that this amplitude variability can be attributed to pre- and/or post-synaptic mechanisms [1–4]. Hunt [1] suggested that the background activities of motor neurons and interneurons in the spinal cord partially account for the fluctuation of the monosynaptic reflex response. In contrast, Rudomin et al. [2,3] reported that the fluctuation originates from the presynaptic input that modulates the signal transmission from Ia fiber to the motor neuron. Meanwhile, Gossard et al. [4] showed that the fluctuation is caused both by presynaptic modulation of the Ia output and by the subthreshold random input from interneurons directly to motor neurons.

On the other hand, Nozaki et al. [5] found that the time series of the H-wave amplitude, which reflects monosynaptic reflex activity, temporally fluctuates with fractal long-range correlation in the soleus muscle (SOL) in healthy human participants at rest. In a later study, Nozaki et al. [6] also showed that higher coherence below 0.2 Hz with zero phase lag exists between the H-wave amplitude sequences in the two legs. This coherence was significantly higher in healthy participants than in individuals with complete or incomplete spinal cord injury [6]. This suggests that the fractal fluctuation in the H-wave amplitudes under the resting condition was accounted for by supraspinal input, but the detailed mechanism underlying this phenomenon remains unclear. Correspondingly, Chang et al. [7] reported that there was no temporal correlation for the monosynaptic reflex sequences in spinalized cats. Therefore, the supraspinal input plays an important role in generating the fractal correlation in the fluctuation of H-wave amplitudes.

Because the supraspinal input sends a similar command to the

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synergistic muscles, a fluctuation of the motor unit (MU) firing rates often occurs in common between the synergistic muscles, a phenomenon termed “common drive [8,9]”. De Luca and Erim [9] previously showed that the fluctuations of the MU firing rates within the tibialis anterior muscle were correlated with each other as an effect of the common drive from the central nervous system (CNS), which showed that the CNS has a simple strategy for controlling the underlying MU activations. Also, De Luca and Erim [10] indicated the existence of the common drive across the synergistic muscles. These findings suggest that the CNS sends a partially common input among the synergistic muscles. In addition, the firing rates of the MUs in the bilateral SOLs represented low-frequency (0–5 Hz) common modulation during postural tasks [11], which corresponded with the coherent fluctuations of the SOL H-reflex in both legs [6]. Accordingly, we hypothesized that fractal long-range correlated components, i.e., relatively slowly changing random components, that were included in the H-wave amplitude fluctuations were shared between the synergistic muscles via the common CNS input.

The purpose of this study was therefore to quantify the correlation of long-range correlation components in the H-wave amplitude sequences between the medial head of the gastrocnemius muscle (MG) and the SOL. For this purpose, we used detrending moving-average cross-correlation analysis (DMCA), which can detect long-range correlation behavior between two nonstationary signals [12]. DMCA has advantages such as its well-established mathematical foundation, wide applicability to nonstationary time series, and fast implementation algorithm. Thus, we employed the DMCA instead of conventional cross-spectral analysis techniques and detrended cross-correlation analysis (DCCA) [13].

2. Methods

2.1. Participants

Eight males volunteered for this study. Their characteristics, given as means (standard deviations (SDs)), were as follows: age 24 (3) years, height 170.8 (3.9) cm, and weight 64.2 (6.2) kg. All participants were right leg dominant. None had experienced any neurological disease. This study was performed in accordance with the Declaration of Helsinki. The study protocol was approved by the Ethics Review Board, Ritsumeikan University Biwako-Kusatsu Campus. Each participant received an explanation of the nature and purpose of the study and gave written informed consent for participation. They were asked to avoid intense exercise, coffee, tea, and alcohol for 24 h before testing.

2.2. Experimental procedures

Each participant underwent a 30-min measurement, where the sequential H-reflex elicitations in the MG and SOL were performed in a manner similar to that used in our previous study [14]. During the measurement, participants were asked to lie on a bed in the supine position, and only their right legs were tested. Before the measurement, the location of the stimulation electrode (Ag/AgCl, sensor area 15 mm^2, gel area 95 mm^2; N-00-S: Ambu, Denmark) and the stimulation intensity for the repetitive H-reflex elicitations were determined. To evoke the H-reflex, the tibial nerve was stimulated at the popliteal fossa by a stimulator (SEN-7203; Nihon-Kohden, Japan). The stimulation current was a unipolar rectangular pulse of length 0.5 ms [15]. The H- and M-waves were recorded using the surface electromyography (EMG) from the MG and SOL in the tested leg. For the EMG measurement, bipolar electrodes (Ag/AgCl, 4-mm pick-up diameter, 20-mm inter-electrode distance) were applied on each muscle. The electrode position was determined according to the SENIAM recommendations (seniam.org). The reference electrode was attached to the lateral malleolus of the tested leg. The EMG signal was differentially amplified, filtered between 1 Hz and 30 kHz (ER-1 Differential Extracellular Amplifier; Cygnus Technology, PA), and continuously digitized at 10 kHz by a 16-bit analog-to-digital converter (PowerLab 16/30; AD Instruments, Sydney, Australia). Because there was very little power in the frequency band above 5 kHz, the aliasing was negligible. In this study, we aimed to assess the temporal correlation of H-wave amplitude fluctuations between the MG and SOL. However, the appropriate intensity of the stimulation current that evoked the H-wave differed between these muscles. Therefore, we employed two different current intensities: one was for H-wave recording in the MG, and the other was for H-wave recording in the SOL. Each intensity was set at 110% of the M-wave generation threshold [14]. Specifically, H-waves for the MG and SOL were alternately evoked with two different stimulation intensities at the frequency of 1 Hz. The two intensities were automatically switched by the stimulator. As a result, the H-wave amplitude time series for each of the MG and SOL was obtained at a sampling frequency of 0.5 Hz, and there was a time lag of 1 s between these sequences.

2.3. Data analysis

The time series of the H-wave peak-to-peak amplitude was obtained for each muscle (Fig. 1). The series was 900 points in length with a sampling frequency of 0.5 Hz and could be considered almost simultaneous. While in actuality a 1-s time lag existed, it was substantially shorter than the length of the long-range fluctuation component (i.e., 12.6 s to 317.0 s, described below) analyzed in the cross-correlation. Also, the optimality of a zero time lag between the two time series was validated using the detrended cross-covariance analysis (see details in [12]).

First, in order to assess the scaling exponent α of the H-wave amplitude fluctuation in each muscle, detrending moving average (DMA) analysis [16–19], an improved version of detrended fluctuation analysis (DFA) [20], was employed. The DMA method can minimize the estimation error of scaling exponent α, which is often caused by the detrending procedure in DFA [21]. The algorithm used in this study was a high-order DMA, described in detail in an earlier report in conjunction with its application to biological signals (heart rate variability) [18]. This method can remove a high-order polynomial trend using a Savitzky-Golay detrending filter [17]. Briefly, the original time series $\{x(i)\}_{i=1}^{N}$ was integrated following the removal of the sample mean:

$$y(i) = \sum_{j=1}^{i} \left(x(j) - \bar{x}\right),$$

where $\{y(i)\}_{i=1}^{N}$ denotes the integrated time series and $\bar{x}$ is the sample mean of $\{x(i)\}$. Then, we calculated the generalized variance relative to the trend, estimated by the moving average polynomial:

$$F^2(n) = (N - n + 1)^{-1} \sum_{i=1+(n-1)/2}^{N-(n-1)/2} \left[y(i) - \tilde{y}_n(i)\right]^2,$$

where $\tilde{y}_n(i)$ is the estimated trend using a Savitzky-Golay detrending filter with a window size of n. Using the Savitzky-Golay filter with a polynomial order m, an arbitrary polynomial curve with order $(m + 1)$ can be traced completely. Thus, performing DMA using a higher-order Savitzky-Golay filter can well eliminate non-stationary trends that are locally approximated by a higher order polynomial. The DMA using the m th order Savitzky-Golay filter is called m th order DMA. Note that the zeroth order Savitzky-Golay filter is the same as the moving average filter, and the zeroth order DMA corresponds to the original DMA. In the present study, the order m was set at 2 [22]. Fig. 2 shows a typical example of DMA analysis for the H-wave amplitude time series in each muscle. The slope in the double logarithmic plot of the root-mean-square deviation ($F(n)$) as a function of the window length (n) indicates the scaling exponent α, which characterizes long-range correlation.

Following the DMA analyses, we applied DMCA [12,23,24], an improved variant of the DCCA [13], in order to quantify the correlation

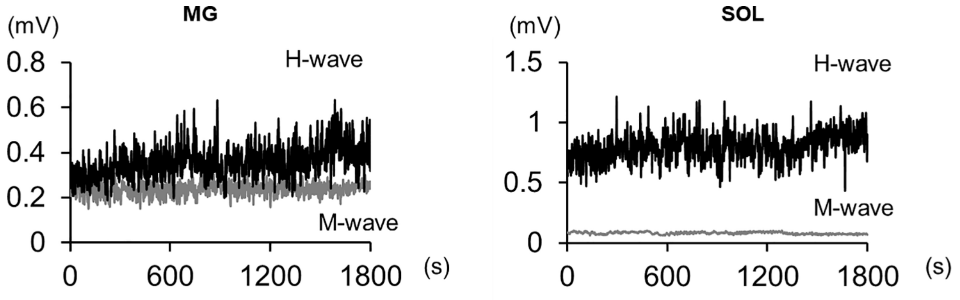

Fig. 1. Original time series of H-wave (black) and M-wave (gray) amplitudes in the medial head of the gastrocnemius muscle (MG) and the soleus muscle (SOL) in a participant.

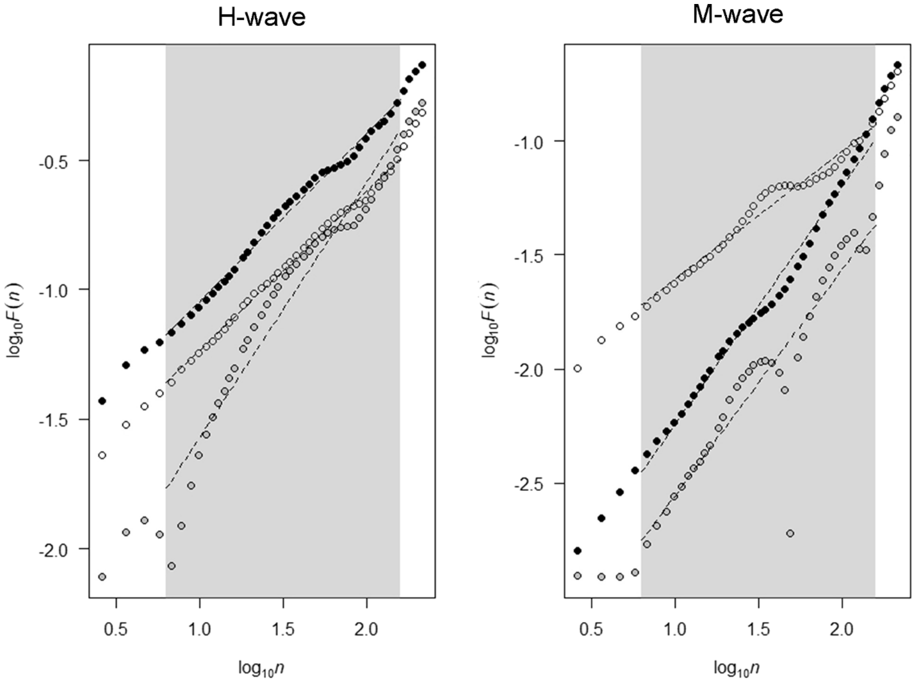

Fig. 2. Detrending moving average (DMA) analysis and detrending moving-average cross-correlation analysis (DMCA) of the H-wave and M-wave amplitude original time series in the MG and SOL, in the same participant as in Fig. 1. The $F(n)$ values for the MG (DMA, open circle), SOL (DMA, black circle), and MG-SOL (DMCA, gray circle) are plotted in a double logarithmic plot. The scaling exponents α and λ were computed as the slope of the regression line (dotted line) for $0.8 \le \log_{10} n \le 2.2$ (gray scale).

between the long-range fractal behavior of two signals. In the same way as for the higher order DMA, we employed a high-order DMCA with Savitzky-Golay detrending filters [12,24], which was previously applied to bivariate biological signals such as those from cardiorespiratory or cardiovascular systems [22,24]. Briefly, the detrended covariance ($F^2_{1,2}(n)$) between two integrated time series $\left\{\left(y^{(1)}[i], y^{(2)}[i]\right)\right\}_{i=1}^{N}$ was calculated for a given window size n as follows:

$$F^2{}_{1,2}(n) = (N-n+1)^{-1} \sum_{i=1+(n-1)/2}^{N-(n-1)/2} \left(y^{(1)}[i] - \widetilde{y}_n^{(1)}[i]\right)\left(y^{(2)}[i] - \widetilde{y}_n^{(2)}[i]\right)$$

where $\widetilde{y}_n^{(l)}[i] (l = 1, 2)$ is a smooth trend included in $y^{(l)}[i]$, approximated by the Savitzky-Golay smoothing filter. The long-range power-law cross-correlation is characterized by scaling exponent λ, which is defined by

$$F^2{}_{1,2}(n) \sim n^{2\lambda}.$$

In the present study, the scaling exponent λ in DMCA was calculated for $0.8 \le \log_{10} n \le 2.2$ (time scale range from 12.6 s to 317.0 s), as shown in Fig. 2. Because the scaling exponent λ does not quantify the strength of correlation, the cross-correlation coefficient $\rho\mathrm{DMCA}(n)$ was calculated as follows [25]:

$$\rho\mathrm{DMCA}(n) = \frac{F^2{}_{1,2}(n)}{\sqrt{F^2{}_1(n)}\sqrt{F^2{}_2(n)}},$$

where $F_1(n)$ and $F_2(n)$ are the square-roots of the detrended variance in DMA for the time series $y^{(1)}$ and $y^{(2)}$, respectively. The two time series are definitely independent when ρDMCA becomes 0 and dependent when ρDMCA becomes 1. The average of $\rho\mathrm{DMCA}(n)$ for $0.8 \le \log_{10} n \le 2.2$ was evaluated in the present study.

Next, to test the existence of significant correlations in the original H-wave amplitude time series, the DMA and DMCA results for the original H-wave amplitude sequences were compared with those for surrogate H-wave amplitude sequences. Two sets of surrogate sequences were created using the TISEAN package [26]: (1) randomly shuffled (Random); (2) randomly shuffled while the power spectrum was approximately preserved using an iterative amplitude adjusted Fourier transform algorithm (IAAFT). The Random data would indicate no temporal correlation, and the IAAFT data would show no cross-correlation because the temporal correspondences between the series are disrupted.

Finally, from the 30-min H-reflex measurement, a time series of the M-wave peak-to-peak amplitude (900 points long with a sampling frequency of 0.5 Hz) was also obtained for each muscle (Fig. 1). The pair of M-wave amplitude sequences was also analyzed by DMA and DMCA

(Fig. 2) in order to investigate whether the electrical properties at a local site influence the DMA and DMCA results for the H-wave amplitude time series.

2.4. Statistical analysis

In each of the H- and M-wave amplitudes, the scaling exponent α for each muscle and the average ρDMCA value were compared between the original, Random, and IAAFT data. All of these comparisons were performed using Friedman tests, followed by Wilcoxon signed-ranks tests with Bonferroni corrections (OriginPro 2019b, OriginLab, Northampton, MA). Statistical significance was set at $P < 0.05$. The data are presented as means (SDs).

3. Results

As shown in a typical example of the DMA analysis (Fig. 2), there was an almost linear increase of $\log_{10}F(n)$ as a function of $\log_{10} n$ for $0.8 \leq \log_{10} n \leq 2.2$, for each of the H-wave amplitude time series in all participants. The group data for the scaling exponent α are summarized in Table 1. The α value was significantly higher for the original data than for its Random data in each muscle ($P = 0.0234$ for each). Furthermore, as a result of the DMA analysis of the M-wave amplitude time series (see the example in Fig. 2), the α value for the original data was significantly higher than that for the Random data in each muscle ($P = 0.0234$ for each, Table 1). Notably, higher α values were observed in all participants for the original H- and M-wave amplitude data compared to the Random data. Similar results to the original data were observed for the IAAFT data, as their power spectra were approximately preserved (Table 1).

On the other hand, the DMCA demonstrated that the group mean of scaling exponent λ between the H-wave amplitude time series in the MG and SOL was 0.92 (0.28). In addition, the λ value for the M-wave amplitude time series was found to be 1.17 (0.18). Fig. 3 shows a typical example of $\rho\mathrm{DMCA(n)}$, which represents the strength of the long-range cross-correlation, for the pair of H-wave amplitude time series in a participant. Because the temporal correspondences between the MG and SOL data were disrupted in the surrogate (Random and IAAFT) data sets, theoretically no cross-correlations were assumed for them. In this example, the mean ρDMCA for $0.8 \leq \log_{10} n \leq 2.2$ was 0.39 for the original data, while it became 0.18 and 0.08 for the Random and IAAFT data, respectively, which is indicative of a long-range cross-correlation with higher strength in the original data. This trend in the H-wave amplitude ρDMCA was observed for all participants. However, this was not the case for the M-wave amplitude (Fig. 4), which had a lower $\rho\mathrm{DMCA(n)}$ value in the original data (mean $\rho\mathrm{DMCA} = 0.01$ in this participant), as did its Random (mean $\rho\mathrm{DMCA} = 0.03$) and IAAFT data (mean $\rho\mathrm{DMCA} = -0.15$). In the group data, the mean ρDMCA for the original H-wave amplitude data was significantly higher than those for the Random and IAAFT data ($P = 0.0234$ for each, Table 2). In contrast, the mean ρDMCA for the M-wave amplitude did not differ among the original, Random, and IAAFT data. These DMCA results showed that there was a substantial, long-range correlation between the H-wave amplitude fluctuations in the MG and SOL.

4. Discussion

The main finding of the present study is that there was a long-range (12.6–317.0 s) power-law (scaling exponent $\lambda = 0.92$ (0.28)) correlation between the H-wave amplitude fluctuations in the MG and SOL. A previous study [10] showed that the firing pattern of the MUs was similar among the synergistic muscles, although this similarity was weaker than that within a single muscle. Additionally, Mochizuki et al. [11] found that the firing rates of the MUs in bilateral SOLs are commonly modulated during quiet standing, where the foot center of pressure fluctuations in the anteroposterior direction are highly correlated between legs. Therefore, on some occasions, each motor neuron pool in synergistic muscles partially shared the drive from the CNS. Nozaki et al. [6] confirmed that the fractal correlation of H-wave amplitude fluctuation in the SOL was stronger in healthy participants than in individuals with spinal cord injury. They also reported that higher coherence with zero phase between the H-wave amplitude fluctuations in the right and left legs was found in healthy participants compared to individuals with spinal cord injury [6]. In the present study, based on these observations, we considered that the long-range power-law correlation between H-wave amplitude fluctuations in the ipsilateral MG and SOL was mainly accounted for by the common input with fractal behavior from the supraspinal level.

On the other hand, in the resting condition, depression of the SOL H-reflex persists up to 10 s after the preceding SOL H-reflex, due to the reduced presynaptic transmitter release in the Ia afferent [27–29]. Therefore, this long-lasting depression would cause long-term memory in the H-wave amplitude and might account for the common slow fluctuation of H-wave amplitudes in the MG and SOL. In fact, in the present study, the Ia afferents of both muscles were stimulated at 1 Hz while the H-wave recordings were made at 0.5 Hz for each muscle. However, it was reported that the SOL H-reflexes repetitively elicited at 1 Hz dramatically decreased their amplitudes only in the first 5 s and then plateaued, likely related to the dynamic behavior of presynaptic transmitter release [30]. Therefore, the postactivation depression with such rapid dynamic behavior would not be a major contributor in the slowly (12.6–317.0 s) changing random components of H-wave amplitude sequences under repetitive stimulations. Furthermore, in Nozaki et al. [5], an additional experiment in two of the five participants indicated that a longer stimulation interval (3 s instead of 1 s) in the consecutive SOL H-reflexes does not affect the fractal long-range correlation in the H-wave amplitude. Hultborn et al. [31] demonstrated that in cats the long-lasting depression of the H-reflex occurs only in the previously activated Ia fibers, suggesting that the postactivation depression would not interact between the MG and SOL. Therefore, the common, fractal input from the supraspinal level, rather than the uncorrelated local depression effect, would be strongly present in the H-wave amplitude fluctuations.

The DMA analysis in the present study demonstrated that the long-range correlation of H-wave amplitude time series exists in the MG as well as the SOL [5,6]. Mathematically, an α value of 0.5 corresponds to an uncorrelated (white noise) process, and an α greater than 0.5 and less than 1.0 indicates persistent long-range correlations (known as a long

Table 1
Results for scaling exponent α obtained using detrending moving average (DMA) analysis for the H- and M-wave amplitude data and their surrogate data in each muscle.

		Original	Random	IAAFT	Friedman test
H-wave	MG	0.76 (0.15) *	0.53 (0.05)	0.80 (0.20) *	${\chi_r}^2(2) = 9.75, P = 0.0076$
	SOL	0.79 (0.10) *	0.49 (0.03)	0.82 (0.12) *	${\chi_r}^2(2) = 13.00, P = 0.0015$
M-wave	MG	0.79 (0.18) *	0.50 (0.02)	0.83 (0.23) *	${\chi_r}^2(2) = 13.00, P = 0.0015$
	SOL	0.88 (0.15) *	0.49 (0.05)	0.91 (0.14) *	${\chi_r}^2(2) = 13.00, P = 0.0015$

Values are group means (SDs). MG, medial head of the gastrocnemius muscle; SOL, soleus muscle; Original, original data; Random, randomly shuffled data; IAAFT, randomly shuffled data with approximately preserved power spectrum.
*Significantly different from Random ($P < 0.05$).

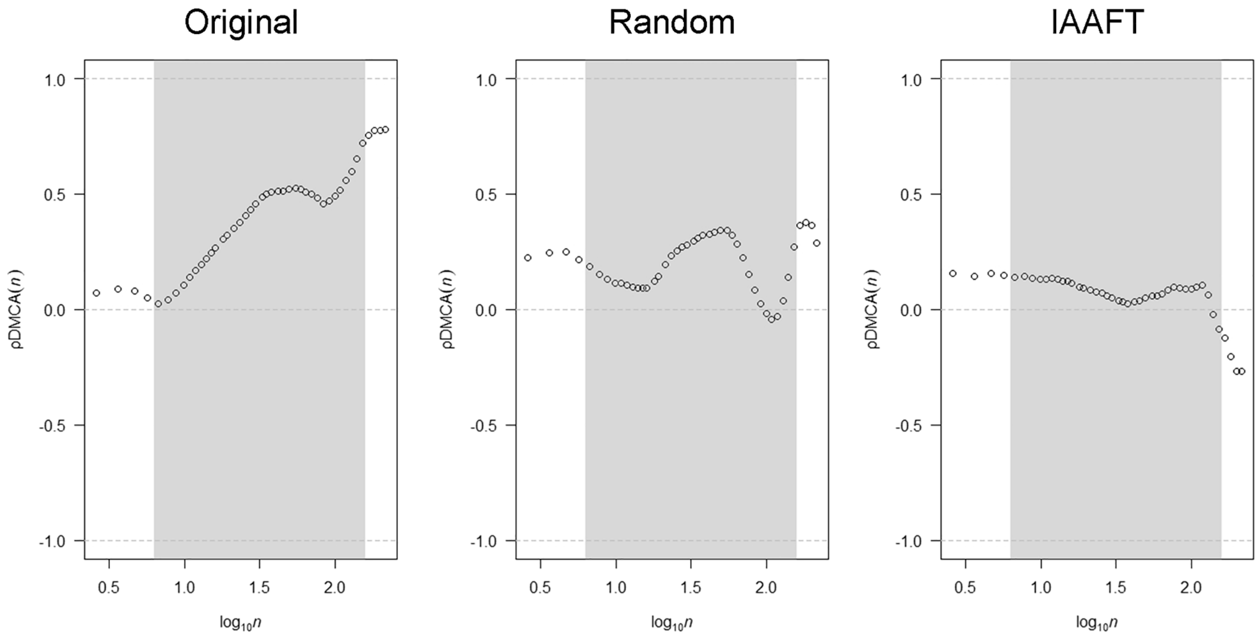

Fig. 3. The correlation coefficient ρDMCA(n) between the MG and SOL for original H-wave amplitude data (Original), randomly shuffled data (Random), and randomly shuffled data with approximately preserved power spectrum (IAAFT) in the same participant as in Figs. 1 and 2.

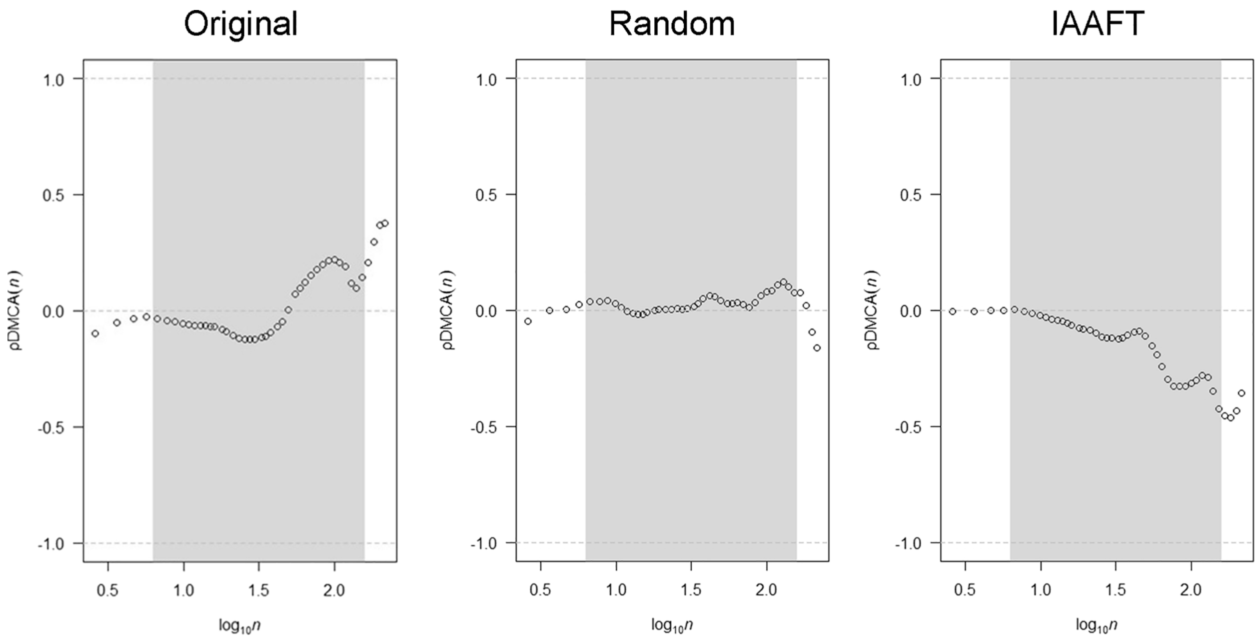

Fig. 4. The correlation coefficient ρDMCA(n) between the MG and SOL for original, Random, and IAAFT M−wave data in the same participant as in Figs. 1, 2, and 3.

Table 2
The correlation coefficient (ρDMCA(n)) averaged for $0.8 \leq \log_{10} n \leq 2.2$ in detrending moving-average cross-correlation analysis (DMCA) between the H-wave amplitude data and between the M-wave amplitude data. The results for each surrogate data are also shown.

Pair for DMCA	Original	Random	IAAFT	Friedman test
H-wave (MG) – H-wave (SOL)	0.50 (0.22)$^{*\#}$	0.22 (0.17)	0.27 (0.20)	$\chi_r^2(2) = 12.00$, $P = 0.0025$
M-wave (MG) – M-wave (SOL)	0.29 (0.23)	0.20 (0.15)	0.13 (0.25)	$\chi_r^2(2) = 2.25$, $P = 0.3247$

Values are group means (SDs).
*Significantly different from Random ($P < 0.05$). #Significantly different from IAAFT ($P < 0.05$).

memory process). In the present study, the group average of scaling exponent α showed comparable values of 0.76 and 0.79 in the MG and SOL, respectively; this showed the presence of persistent long-range power-law correlations in both muscles. However, the proportion of fast muscle fibers is higher in the MG than in the SOL [32], where the electrical properties of alpha motor neurons such as input resistance and rheobase are different between type S and type F MUs [33]. In addition, the functional role seems to be different among these triceps surae muscles. For example, the SOL shows continuous activity, while the MG demonstrates phasic activity during quiet standing [34]. Therefore, there is still a possibility that the dynamic property of temporal fluctuation in the alpha motor neuron excitability is affected by differences in the electrical properties and/or functional roles between these muscles.

Nevertheless, the present study employed only a fixed current intensity at 110% of the M-wave generation threshold. Therefore, the MUs activated by the Ia afferent input might not be optimal for finding such an intrinsic difference between muscles, as the slower MUs are primarily recruited in H-reflex [35]. Also, the magnitude of the H-wave amplitude relative to the maximal M-wave amplitude (% of Mmax) affects the sensitivity of the H-wave amplitude to changes in alpha motor neuron pool excitability [36]. We expect to perform a future systematic investigation with different stimulation intensities well-defined by the % of Mmax in order to quantitatively assess the intrinsic dynamic properties in these muscles.

The M-wave amplitude also showed a long-range (12.6–317.0 s) correlation (Table 1), contrary to the previous study [5]. The largely different time scale (about 3–30 s in [5]) might have caused this contradiction. In the present study, the correlation would be generated at a local site such as the neuromuscular junction [37]. Nevertheless, the M-wave amplitude was not correlated between muscles (Table 2), showing that such local fractal dynamics cannot account for the cross-correlation found in the H-wave amplitude (Table 2).

This study has several limitations. First, we employed a single pair of electrodes for the EMG measurement in each muscle. However, recent studies have shown region-specific responses within the MG and SOL [38,39]. As there is no evidence that the fractal correlation embedded in the monosynaptic reflex is common or region-specific within a single muscle, a future systematic investigation with multiple electrodes for different muscle regions [38,39] is warranted in order to explore more precisely how the fractal correlation of monosynaptic reflex is shared within and between the muscles. Second, in each muscle, the intermediate responses were induced by stimulation of the other muscle, for technical reasons. From the present data, we cannot estimate the influence of the intermediate responses on the behavior of the H-wave amplitude. Recently, Vieira et al. [40] located a cathode on the branch of the tibial nerve leading to the MG, downstream of the stimulation site used in this study, in order to exclusively stimulate the MG. While stimulation of the SOL must still activate the MG, the intermediate responses would be removed from the SOL using the stimulation method and could be helpful to further elucidate the present result. Third, the intermediate responses in each muscle might have affected the H-wave signal in the other muscle via EMG cross-talk. As mentioned above, in future work, exclusive stimulation of the MG [40] would also reduce the EMG cross-talk from the SOL to the MG. Furthermore, the cross-talk from the MG to the SOL may be evaluated using multiple electrodes on the SOL [38]. Through these methods, we may be able to assess the possible influence of the EMG cross-talk on the present result.

5. Conclusion

A persistent long-range power-law correlation of the H-wave amplitude time series was found between the MG and SOL. These cross-correlated fractal components could be due to the common input with fractal behavior from the supraspinal level.

CRediT authorship contribution statement

Chinami Taki: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Akio Nakata:** Formal analysis, Software, Writing - review & editing. **Naruhiro Shiozawa:** Methodology, Investigation, Writing - review & editing. **Ken Kiyono:** Formal analysis, Software, Writing - review & editing. **Tetsuya Kimura:** Conceptualization, Investigation, Writing - original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C.C. Hunt, Temporal fluctuation in excitability of spinal motoneurons and its influence on monosynaptic reflex response, J. Gen. Physiol. 38 (1955) 801–811.
[2] P. Rudomin, H. Dutton, Effects of presynaptic and postsynaptic inhibition on the variability of the monosynaptic reflex, Nature 216 (5112) (1967) 292–293.
[3] P. Rudomin, R.E. Burke, R. Nunez, J. Madrid, H. Dutton, Control by presynaptic correlation: a mechanism affecting information transmission from Ia fibers to motoneurons, J. Neurophysiol. 38 (1975) 267–284.
[4] J.P. Gossard, M.K. Floeter, Y. Kawai, R.E. Burke, T. Chang, S.J. Schiff, Fluctuations of excitability in the monosynaptic reflex pathway to lumbar motoneurons in the cat, J. Neurophysiol. 72 (3) (1994) 1227–1239.
[5] D. Nozaki, K. Nakazawa, Y. Yamamoto, Fractal correlation in human H-reflex, Exp. Brain Res. 105 (1995) 402–410.
[6] D. Nozaki, K. Nakazawa, Y. Yamamoto, Supraspinal effects on the fractal correlation in human H-reflex, Exp. Brain Res. 112 (1996) 112–118.
[7] T. Chang, S.J. Schiff, T. Sauer, J.P. Gossard, R.E. Burke, Stochastic versus deterministic variability in simple neuronal circuits: I, Monosynaptic spinal cord reflexes, Biophys J 67 (1994) 671–683.
[8] C.J. De Luca, R.S. LeFever, M.P. McCue, A.P. Xenakis, Control scheme governing concurrently active human motor units during voluntary contractions, J. Physiol. 329 (1982) 129–142.
[9] C.J. De Luca, Z. Erim, Common drive of motor units in regulation of muscle force, Trends Neurosci. 17 (7) (1994) 299–305.
[10] C.J. De Luca, Z. Erim, Common drive in motor units of a synergistic muscle pair, J. Neurophysiol. 87 (4) (2002) 2200–2204.
[11] G. Mochizuki, J.G. Semmler, T.D. Ivanova, S.J. Garland, Low-frequency common modulation of soleus motor unit discharge is enhanced during postural control in humans, Exp. Brain Res. 175 (4) (2006) 584–595.
[12] A. Nakata, M. Kaneko, T. Shigematsu, S. Nakae, N. Evans, C. Taki, T. Kimura, K. Kiyono, Generalized theory for detrending moving-average cross-correlation analysis: A practical guide, Chaos, Solitons & Fractals: X 3 (2019) 1–12.
[13] B. Podobnik, H.E. Stanley, Detrended cross-correlation analysis: a new method for analyzing two nonstationary time series, Phys. Rev. Lett. 100 (2008), 084102.
[14] C. Taki, N. Shiozawa, T. Kimura, Application of minute electrical noise to muscle proprioception modulates excitability of alpha motor neuron group, Advanced, Biomed. Eng. 6 (2017) 37–41.
[15] M. Panizza, J. Nilsson, M. Hallett, Optimal stimulus duration for the H reflex, Muscle Nerve 12 (7) (1989) 576–579.
[16] E. Alessio, A. Carbone, G. Castelli, V. Frappietro, Second-order moving average and scaling of stochastic time series, European Physical Journal B 27 (2002) 197–200.
[17] A. Carbone, K. Kiyono, Detrending moving average algorithm: Frequency response and scaling performances, Phys. Rev. E 93 (2016), 063309.
[18] Y. Tsujimoto, Y. Miki, S. Shimatani, K. Kiyono, Fast algorithm for scaling analysis with higher-order detrending moving average method, Phys. Rev. E 93 (2016), 053304.
[19] N. Vandewalle, M. Ausloos, Crossing of two mobile averages: A method for measuring the roughness exponent, Phys. Rev. E 58 (1998) 6832.
[20] C.-K. Peng, S. Havlin, H.E. Stanley, A.L. Goldberger, Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series, Chaos 5 (1) (1995) 82–87.
[21] K. Kiyono, Y. Tsujimoto, Nonlinear filtering properties of detrended fluctuation analysis, Phys. A 462 (2016) 807–815.
[22] A. Nakata, M. Kaneko, C. Taki, N. Evans, T. Shigematsu, T. Kimura, K. Kiyono, Assessment of long-range cross-correlations in cardio-respiratory and cardiovascular interactions, Phil Trans R Soc A, in press.
[23] L.-Y. He, S.-P. Chen, A new approach to quantify power-law cross-correlation and its application to commodity markets, Phys. A 390 (21-22) (2011) 3806–3814.
[24] Y. Tsujimoto, Y. Miki, Y. Watanabe, J. Hayano, Y. Yamamoto, T. Nomura, K. Kiyono, Fast algorithm of long-range cross-correlation analysis using Savitzky-Golay detrending filter and its application to biosignal analysis. 2017 International Conference on Noise and Fluctuations, 2017.
[25] L. Kristoufek, Detrending moving-average cross-correlation coefficient: Measuring cross-correlations between non-stationary series, Phys. A 406 (2014) 169–175.
[26] R. Hegger, H. Kantz, T. Schreiber, Practical implementation of nonlinear time series methods: The TISEAN package, Chaos 9 (1999) 413–435.
[27] C. Crone, J. Nielsen, Methodological implications of the post activation depression of the soleus H-reflex in man, Exp. Brain Res. 78 (1989) 28–32.
[28] R.B. Stein, A.K. Thompson, Muscle reflexes in motion: how, what, and why? Exerc. Sport Sci. Rev. 34 (2006) 145–153.
[29] R.B. Stein, K.L. Estabrooks, S. McGie, M.J. Roth, K.E. Jones, Quantifying the effects of voluntary contraction and inter-stimulus interval on the human soleus H-reflex, Exp. Brain Res. 182 (3) (2007) 309–319.
[30] R.A. Mezzarane, A.F. Kohn, Bilateral soleus H-reflexes in humans elicited by simultaneous trains of stimuli: symmetry, variability, and covariance, J. Neurophysiol. 87 (4) (2002) 2074–2083.

[31] H. Hultborn, M. Illert, J. Nielsen, A. Paul, M. Ballegaard, H. Wiese, On the mechanism of the post-activation depression of the H-reflex in human subjects, Exp. Brain Res. 108 (1996) 450–462.

[32] M.A. Johnson, J. Polgar, D. Weightman, D. Appleton, Data on the distribution of fibre types in thirty-six human muscles, An autopsy study, J Neurol Sci 18 (1) (1973) 111–129.

[33] J.W. Fleshman, J.B. Munson, G.W. Sypert, W.A. Friedman, Rheobase, input resistance, and motor-unit type in medial gastrocnemius motoneurons in the cat, J. Neurophysiol. 46 (6) (1981) 1326–1338.

[34] K. Masani, M.R. Popovic, K. Nakazawa, M. Kouzaki, D. Nozaki, Importance of body sway velocity information in controlling ankle extensor activities during quiet stance, J. Neurophysiol. 90 (6) (2003) 3774–3782.

[35] F. Buchthal, H. Schmalbruch, Contraction times of twitches evoked by H-reflexes, Acta Physiol Scand 80 (1970) 378-382.

[36] C. Crone, H. Hultborn, L. Mazieres, C. Morin, J. Nielsen, E. Pierrot-Deseilligny, Sensitivity of monosynaptic test reflexes to facilitation and inhibition as a function of the test reflex size: a study in man and the cat, Exp. Brain Res. 81 (1990) 35–45.

[37] S.B. Lowen, S.S. Cash, M.-M. Poo, M.C. Teich, Quantal neurotransmitter secretion rate exhibits fractal behavior, J. Neurosci. 17 (15) (1997) 5666–5677.

[38] A. Botter, T.M. Vieira, Optimization of surface electrodes location for H-reflex recordings in soleus muscle, J. Electromyogr. Kinesiol. 34 (2017) 14–23.

[39] T.M. Vieira, A. Botter, M.A. Minetto, E.F. Hodson-Tole, Spatial variation of compound muscle action potentials across human gastrocnemius medialis, J. Neurophysiol. 114 (3) (2015) 1617–1627.

[40] T.M.M. Vieira, M.A. Minetto, E.F. Hodson-Tole, A. Botter, How much does the human medial gastrocnemius muscle contribute to ankle torques outside the sagittal plane? Hum. Mov. Sci. 32 (4) (2013) 753–767.