Continuous Wavelet Transform Analysis of Surface Electromyography for Muscle Fatigue Assessment on the Elbow Joint Motion

TRIWIYANTO[1,3], *Oyas WAHYUNGGORO*[1], *Hanung ADI NUGROHO*[1], *HERIANTO*[2]

[1]Department of Electrical Engineering & Information Technology, Faculty of Engineering, Universitas Gadjah Mada, Grafika No. 2, Yogyakarta, Indonesia
[2]Department of Mechanical & Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada, Grafika No. 2, Yogyakarta, Indonesia
[3]Department of Electromedical Engineering, Politeknik Kesehatan Surabaya, Pucang Jajar Timur No. 10, Surabaya, Indonesia

triwiyanto123@gmail.com, oyas@ugm.ac.id, adinugroho@ugm.ac.id, herianto@ugm.ac.id

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Abstract. *Studying muscle fatigue plays an important role in preventing the risks associated with musculoskeletal disorders. The effect of elbow-joint angle on time-frequency parameters during a repetitive motion provides valuable information in finding the most accurate position of the angle causing muscle fatigue. Therefore, the purpose of this study is to analyze the effect of muscle fatigue on the spectral and time-frequency domain parameters derived from electromyography (EMG) signals using the Continuous Wavelet Transform (CWT). Four male participants were recruited to perform a repetitive motion (flexion and extension movements) from a non-fatigue to fatigue condition. EMG signals were recorded from the biceps muscle. The recorded EMG signals were then analyzed offline using the complex Morlet wavelet. The time-frequency domain data were analyzed using the time-averaged wavelet spectrum (TAWS) and the Scale-Average Wavelet Power (SAWP) parameters. The spectral domain data were analyzed using the Instantaneous Mean Frequency (IMNF) and the Instantaneous Mean Power Spectrum (IMNP) parameters. The index of muscle fatigue was observed by calculating the increase of the IMNP and the decrease of the IMNF parameters. After performing a repetitive motion from non-fatigue to fatigue condition, the average of the IMNF value decreased by 15.69 % and the average of the IMNP values increased by 84 %, respectively. This study suggests that the reliable frequency band to detect muscle fatigue is 31.10–36.19 Hz with linear regression parameters of 0.979* $mV^2 \cdot Hz^{-1}$ *and 0.0095* $mV^2 \cdot Hz^{-1}$ *for* R^2 *and slope, respectively.*

Keywords

CWT, elbow joint angle, EMG, muscle fatigue, wavelet.

1. Introduction

In everyday life, when the limb performs an intensive repetitive motion, the muscle can experience muscle fatigue. The muscle fatigue is a condition in which the muscle cannot sustain the force on the given certain task. Muscle fatigue can provide a useful information which needs to be considered in the area of ergonomic, robotic exoskeleton based on EMG control, and sport. Furthermore, the muscle fatigue can be used to prevent the muscle disorder. Several techniques have been used to determine the muscle fatigue, and analyzing the EMG signals are widely used to indicate the muscle fatigue [1]. When the muscle is in the fatigue condition, it is proved that the spectral parameters (frequency and amplitude) of the EMG signal will change [1]. Basmajian and De Luca had reported the results of their study, where during constant force contraction, the amplitude of the EMG signal increased and both mean and median frequency shifted to the lower values [1]. Generally, a conventional method to measure the spectral parameters of the EMG signal is by utilizing the Fast Fourier Transform (FFT) method. In this case, the EMG signal, however, is assumed to be in the stationary condition which the muscle fatigue is determined by performing constant force or isometric contraction [2] on the subject's limb. Determination of the muscle fatigue in the dynamic motion of the limb is closely related to daily activities. During the dynamic motion, the muscle length changes [1] in accordance with the limb joint angle, and for this issue, the non-stationary characteristic of the EMG signal increases [3].

The studies that addressed the muscle fatigue in the dynamic contraction have been conducted by several previous researchers. Gonzales et al. determined the muscle fatigue during a repetitive motion on the knee using the mean and variance of instantaneous frequency based on Choi–William distribution [4]. Chowdhury et al. used Discrete Wavelet Transform (DWT) to determine the muscle fatigue on the neck and shoulder during a repetitive motion [5]. In their study, the changes in the spectral parameter were observed by calculating the DWT coefficients. Karthick and Ramakrishnan proposed a method to observe the progression of the muscle fatigue during the elbow motion in the flexion and extension [6] by utilizing the time-frequency distribution. Triwiyanto et al. proposed the DWT analysis of the EMG signal to conclude which level of decomposition is mostly determined for the muscle fatigue in the dynamic motion [7]. The models used in the previous studies have not discussed the relationship between the elbow joint angle and the time-frequency parameters when the muscle was in the fatigue condition.

It is obvious that the EMG signals have the non-stationary characteristic which means that the frequency of the EMG signal changes by the time. In this case, the EMG signals analysis using the CWT becomes the most suitable method compared to the FFT. Therefore, to address the limitations that have been mentioned in the previous studies, a new method needs to be presented for investigating the relationship between the elbow joint angle, and the spectral and time-frequency parameters of the EMG signal when the muscle is in the non-fatigue and fatigue condition. The purpose of this study is to analyze the effect of the muscle fatigue on the spectral and time-frequency parameters using the CWT. The specific objectives of the study are:

- to calculate the linear regression parameters,
- to investigate the effect of the elbow joint angle on the time-frequency parameters in the non-fatigue and fatigue condition, and
- to test the significant difference of the power spectrum density between non-fatigue and fatigue conditions.

2. Theoretical Background

Wavelet analysis is a method to decompose the signal into several parts of the signal based on wavelet basis function. A wavelet function, $\psi_{\tau,s}(t)$, is built based on a mother wavelet function composed of scaling and translation parameters. In this case, s refers to scaling parameter related to the frequency of the signal and τ is translation parameter. The wavelet function is written as follows [8]:

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right), \quad s,\tau \in \mathbb{R}, s \neq 0. \tag{1}$$

The Continuous Wavelet Transform (CWT) of the signal, $x(t)$, is written as follows [8]:

$$\psi_{\tau,s}(t) = \int_{-\infty}^{\infty} x(t)\frac{1}{\sqrt{|s|}}\psi^{*}\left(\frac{t-\tau}{s}\right)\mathrm{d}t. \tag{2}$$

The CWT function on Eq. (2) is composed of the scaling, translation, wavelet function $\psi\left(\frac{t-\tau}{s}\right)$, and the signal $x(t)$. In order to analyze the EMG signal, the function $x(t)$ in Eq. (2) can be substituted by the EMG signals. In this study, the Morlet mother wavelet was used to implement the CWT. The complex-Morlet mother wavelet is defined as follows [8]:

$$\psi = \pi^{-\frac{1}{4}}\left(\mathrm{e}^{\mathrm{i}2\pi \mathrm{f}_0 t} - \mathrm{e}^{-\frac{(2\pi \mathrm{f}_0)^2}{2}}\right)\mathrm{e}^{-\frac{t^2}{2}}, \tag{3}$$

where f_0 indicates the Morlet frequency constant ($\mathrm{f}_0 = 0.849$).

The local Power Spectrum Density (PSD) of the CWT for a certain scale range is measured using the Scaled-Average Wavelet Power (SAWP), as shown in Eq. (4) [9]:

$$\overline{W}_n^2 = \frac{\delta_s \delta_\tau}{C_\delta}\sum_{s=s_1}^{s_2}\frac{|W_n(s)|^2}{s}, \tag{4}$$

where s_1 and s_2 indicate the ranges of the CWT scale, C_δ indicates the coefficient of the mother wavelet, δ_s is the increment of the scale, δ_τ is the time translation of the mother wavelet and W_n is the CWT coefficient. The global scale PSD is measured for all ranges of the scale. A local PSD for the short period of time is measured using the Time-Averaged Wavelet Spectrum (TAWS) described as follows [9]:

$$\overline{W}^2(s) = \frac{1}{N}\sum_{n=0}^{N-1}|W_n(s)|^2, \tag{5}$$

where W_n is the CWT coefficient, and n and N are the specific time range to average the CWT coefficients.

3. Materials and Method

3.1. Participants

Four healthy male volunteers (age: 22.4 ± 3.2 years old, weight: 65.4 ± 5.6 kg, height: 169 ± 4.2 cm) who had no history of the muscular disorder were recruited in this study. Before the data collection, the subjects were recommended not to do any hard work that could harm the elbow joint. Furthermore, the subjects were given the explanation how to do the movements of flexion and extension and told any potential risks that might occur during the experiment.

Fig. 1: The exoskeleton frame to synchronize the elbow joint motion (flexion and extension).

3.2. Equipment

In this study, the EMG signal was collected using one channel EMG system consists of pre-amplifier, band pass filter with the cut-off frequency of 20 and 500 Hz, adjustable gain amplifier and summing amplifier. The EMG signal was collected using three surface electrodes (Ag/AgCl, size: 57×48 mm, Ambu, Bluesensor R, Malaysia). Two electrodes were placed on biceps muscle and one electrode was placed on hand as a common ground electrode. An exoskeleton frame was used to synchronize the elbow joint motion (Fig. 1). The elbow joint angle was collected using a linear potentiometer. One kilogram of the load was placed on the edge of the exoskeleton frame.

3.3. Data Collection

The EMG signal covers frequency in the range of 0 to 500 Hz, while the range of the dominant frequency falls between 50 and 150 Hz [10]. The EMG signal and elbow joint position were collected with a sampling frequency of 1000 Hz [11] and [12]. The choice of this sampling frequency was in accordance with the Nyquist rule [13]. Furthermore, the application program developed using Borland Delphi Professional (Version 7.0, Borland Software Corporation, Scotts Valley, California, USA) was used to acquire the EMG signal and CWT analysis.

During the flexion and extension motion from 0 to 120 degrees, the EMG signal and the elbow joint angle were recorded for off-line data analysis. In the data collection process, subjects were instructed to perform repetitive motion until they were perceived in fatigue conditions. The condition was indicated by the subject's elbow that could not perform the flexion and extension movements.

3.4. Data Processing

The EMG signal and angle data were processed offline using the Borland Delphi Professional (Version 7.0, Borland Software Corporation, Scotts Valley, California, USA), see Fig. 2. Four cycles of flexion and extension motion assigned by T1, T5, T10, and T15 were selected from the EMG data. The T1, T5, T10, and T15 were the cycles that were measured in the first minute, fifth minute, tenth minute, and last minute, respectively. T1 would be assumed as a time location of the non-fatigue condition and T15 denoted as a time location of the fatigue condition. Each cycle of motion was analysed using the CWT. In this study, the CWT implementation used the complex Morlet wavelet which was widely accepted in the EMG analysis [14], [15] and [16]. The coefficients of the CWT were calculated with the scale of 100 with the delta scale (δ_s) of 0.002. The mother wavelet was shifted with the total translation (τ_{total}) of 360. The delta translation (δ_τ) is calculated as follows:

$$\delta_\tau = \frac{(N-1)}{f_s \tau_{\text{total}}}, \qquad (6)$$

where f_s is the frequency sampling in Hz, N is the number of the sample point and τ_{total} is the number of total translation. The following time-frequency and spectral parameters were calculated:

- Scale-Average Wavelet Power (SAWP) is the average of PSD for the specific range of the scale band. In this study, the scales range to be analysed was from 0.002 to 0.052. The scales were divided into 10 bands in which each band has the scale length of 0.005. These ten bands were denoted by the

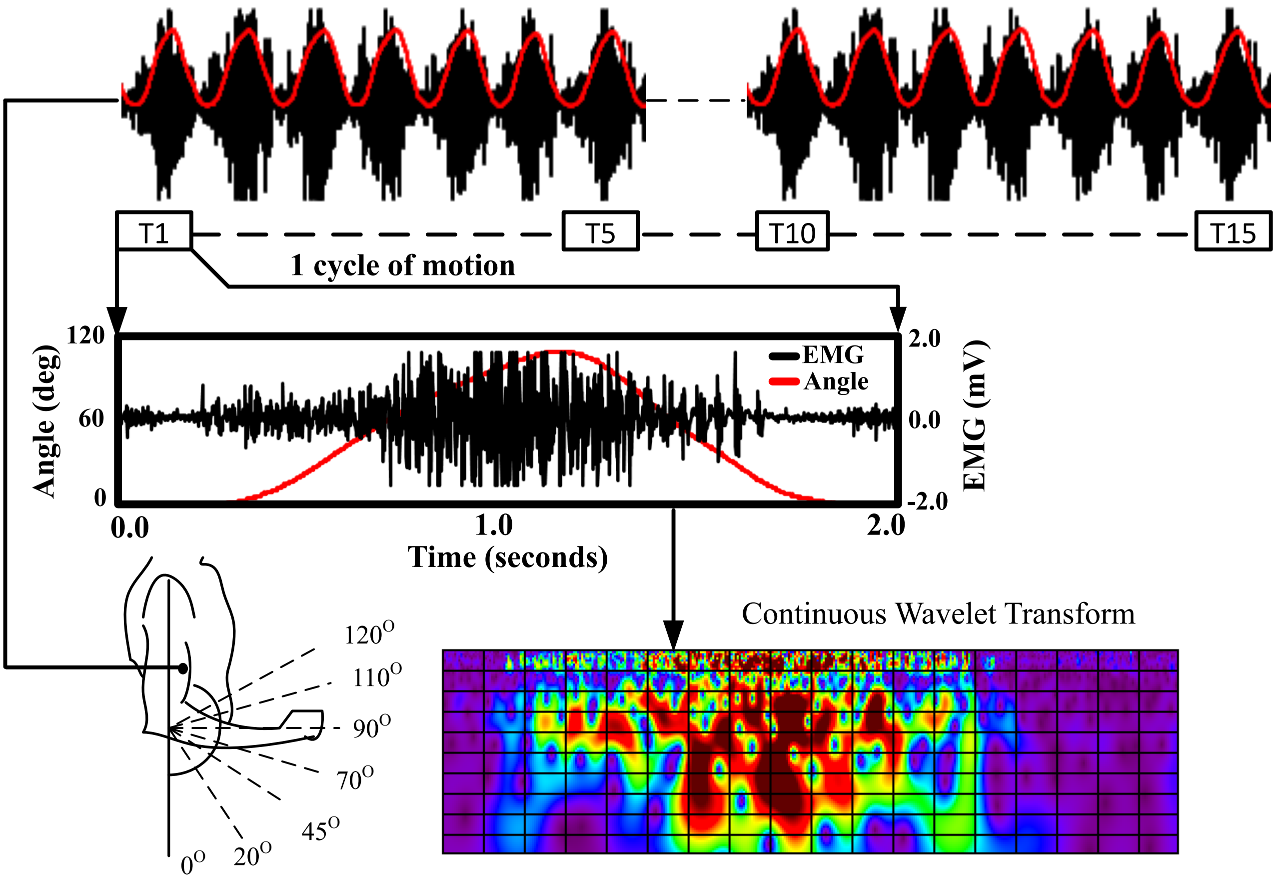


Fig. 2: The illustration of the EMG data processing. Four cycles of the EMG signal indicated by T1, T5, T10, and T15 was analyzed using the CWT. The black line is the EMG signal and the red line is the elbow joint angle.

1^{st} to 10^{th} bands (for example, the 1^{st} band had the scale range of 0.002 to 0.007). The SAWS was calculated based on Eq. (4).

- Time-Average Wavelet Spectrum (TAWS) is the average of PSD for the specific length of the translation. In this study, the number of translation was 360. If the translation length was 20, the number of the TAWS was 18. The TAWS is calculated based on Eq. (5).

- Instantaneous Mean Frequency (IMNF) [6] is calculated to obtain the mean power of frequency at an instant time. The IMNF is formulated as follows:

$$IMNF(\tau) = \frac{\sum_{f_1}^{f_2} f\,|CWT\,(s,\tau)|^2}{\sum_{f_1}^{f_2} |CWT\,(s,\tau)|^2}, \qquad (7)$$

where f_1 denotes the lowest frequency and f_2 denotes the highest frequency and $|CWT|$ is the absolute of the CWT coefficients. The f_1 and f_2 were determined based on the frequency range of the processed EMG signal ($f_1 = 20$ Hz and $f_2 = 500$ Hz).

- Instantaneous Mean Power (IMNP) is the mean of PSD at an instant time [6].

$$IMNP = \frac{1}{N}\sum |CWT\,(s,\tau)|^2, \qquad (8)$$

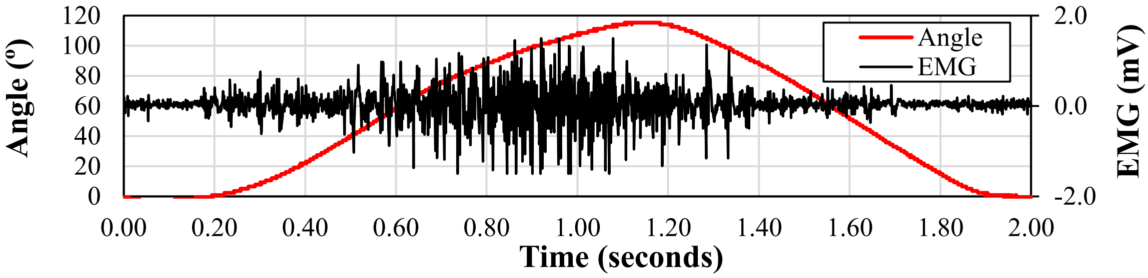
where N indicates the number of scale and $|CWT|$ indicates the absolute of the CWT coefficients.

3.5. Statistical Analysis

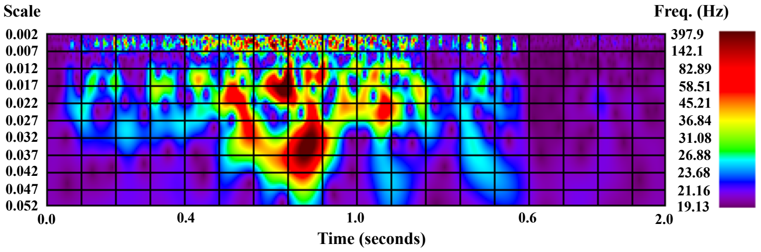
Muscle fatigue affected the spectral and time-frequency parameters of the EMG signal. The significant difference of the parameters was examined using the one way single factor ANOVA with the confidence level of 95 % for T1, T5, T10 and T15 cycle. The effect of the muscle fatigue was significantly indicated by p-value. If the p-value is less than 0.05, then it indicates that the muscle fatigue has significantly affected.

4. Results and Discussion

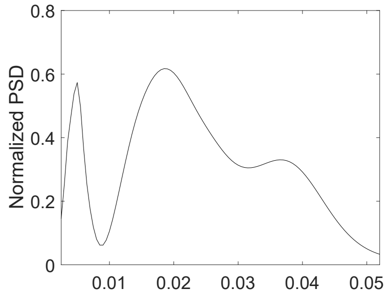
In consideration to the purpose of the study, the change in the spectral parameters (the frequency and magni-



(a) The EMG signal during the flexion and extension motion with the motion period of 2 seconds (the black line is the EMG signal and the red line is the elbow joint angle).

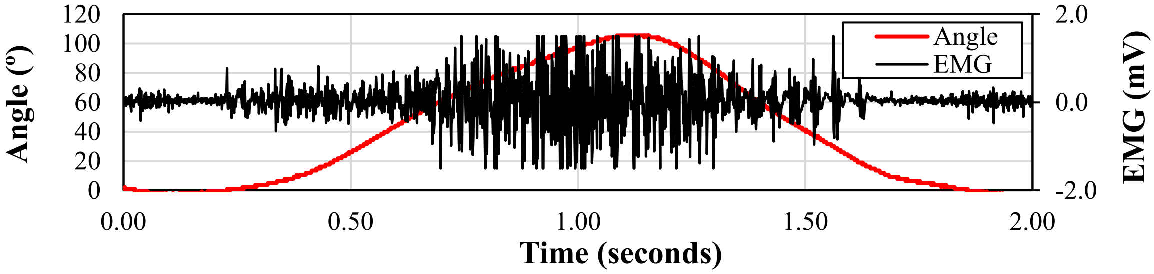


(b) The contour of the CWT coefficients.

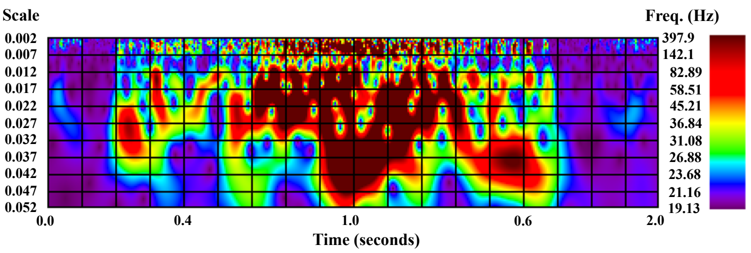


(c) The global wavelet spectrum.

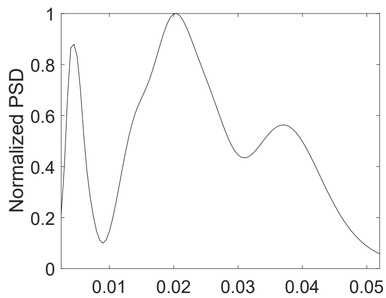
Fig. 3: The typical example of one cycle of the flexion and extension motion which was measured at the first cycle (T1) in the non-fatigue condition.



(a) The EMG signal during the flexion and extension motion with the motion period of 2 seconds (the black line indicates the EMG signal and the red line indicates the elbow joint angle).



(b) The contour of the CWT coefficients.



(c) The global wavelet spectrum.

Fig. 4: The typical cycle of flexion and extension motion which was measured in the last cycle (T15) in the fatigue condition.

tude of power spectrum) was analyzed using the CWT. In the non-fatigue condition (Fig. 3), the averages of the IMNF and IMNP for all of the scale and time are 70.37 ± 10.16 Hz and 0.0165 ± 0.0094 mV^2, respectively. After a repeated flexion and extension movements, the muscle will be in the fatigue condition and the magnitude of the power spectrum increased significantly. Thus, the contour of the wavelet power is wider compared to that in the non-fatigue condition, see Fig. 4(b). Therefore, the averages of the spectral parameters also changed. The averages of the IMNF and IMNP for all of the scale and time in the fatigue condition are 60.83 ± 13.95 Hz and 0.1039 ± 0.084 mV^2, respectively. The average of the IMNF decreased by 15.69 % and the average of the IMNP increased by 84.14 %. These results, i.e. the decrease of the frequency and the increase of the power, are in line with the previous study conducted by Basmajian and De Luca [1]. Similar results were also observed by Karthick and Krishnan which showed that the IMNF and IMDF of EMG signal decrease from non-fatigue to fatigue condition [6].

The Global Wavelet Spectrum (GWS) was calculated based on the average of the PSD for the total time range of 2 seconds as shown in Fig. 5.

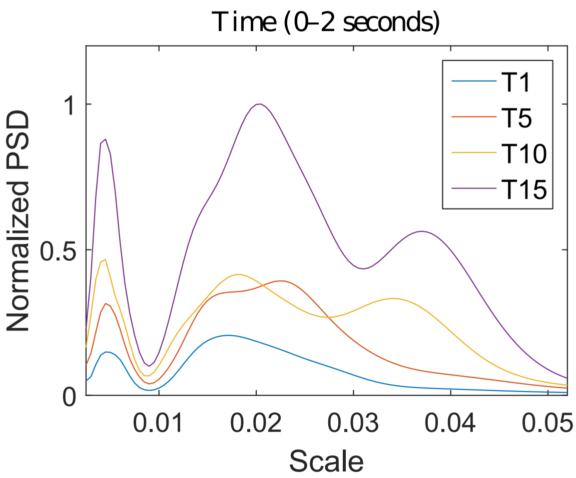


Fig. 5: The global wavelet spectrum for the 2 second duration.

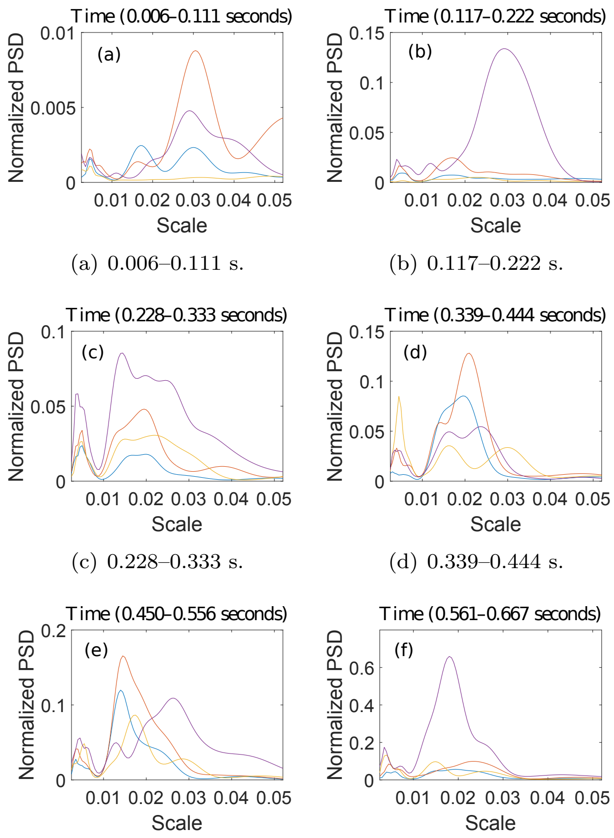
Figure 5 shows that the highest magnitude of the global wavelet spectrum was in the center of scales: 0.017 (58.54 Hz), 0.0175 (56.87 Hz), 0.0185 (53.8 Hz), and 0.020 (49.76 Hz) for the time of T1, T5, T10 and T15, respectively. The GWS in the scale range of 0.002 to 0.008 showed a consistent increase from non-fatigue (T1) to fatigue condition (T15). The time of T1 shows the lowest magnitude of the GWS. It was the first cycle of the EMG measurement (at first minute) and was assumed as a non-fatigue condition. It was followed by T5, T10, and T15. For all of the scale, T15 had the highest GWS. The average of PSD from T1 to T15 increased significantly ($p < 0.05$) about 84.17 %. It was also observed in Fig. 5 in which the frequency changed to lower frequency by 10.48 %, from non-fatigue to fatigue condition. This phenomenon was in line with the Basmajian and de Luca's report. In their study on the assessment of the muscle fatigue, the frequency changed to the lower value and the amplitude increased significantly [1].

The Time-Averaged Wavelet Spectrum (TAWS) and the Scale-Averaged Wavelet Spectrum (SAWS) was calculated to find the specific time location of the spectral parameters.

4.1. Time-Averaged Wavelet Spectrum

Time-Averaged Wavelet Spectrum (TAWS) is calculated according to Eq. (5). The TAWS was calculated for a specific range of time, which was aimed to find the specific time and frequency location related to the elbow joint angle and the muscle fatigue condition. In order to perform the TAWS calculation, the 2 seconds period of the cycle was divided into 18 ranges of time.

Figure 6 shows that the magnitude of the PSD in the time ranges of 0.006–0.111 seconds, 0.117–0.222 seconds, 0.228–0.333 seconds, 0.339–0.444 seconds, 0.450–0.556 seconds, 1.672–1.778 seconds, 1.783–1.889 seconds, and 1.894–2 seconds are smaller compared to the others time range. In the time range of 0–0.556 seconds (Fig. 6(a), Fig. 6(b), Fig. 6(c), Fig. 6(d) and Fig. 6(e)), the TAWS of T1, T5, T10, and T15 showed small PSD ($<\sim 0.2$), except in the time range of 0.561–0.667 sec-



(a) 0.006–0.111 s. (b) 0.117–0.222 s.

(c) 0.228–0.333 s. (d) 0.339–0.444 s.

(e) 0.450–0.556 s. (f) 0.561–0.667 s.

Fig. 6: The TAWS for the time range.

onds. This was in accordance with the angle of the elbow joint at 50–70°. In the fatigue condition (T15), the TAWS tended to show a higher PSD than T1, T5 and T10 (Fig. 6(b), Fig. 6(c) and Fig. 6(f)).

Figure 7 shows the shift of the PSD to the higher scale value, from 0.017 (58.54 Hz) to 0.022 (45.24 Hz), from non-fatigue to fatigue condition. The TAWS increased significantly (p-value< 0.05) from T1 to T5, T1 to T10 and T1 to T15. Among the Fig. 7, Fig. 8, Fig. 9 and Fig. 10, Fig. 10 shows the highest PSD at the scale of 0.022 (equal to the frequency of 46.29 Hz).

The TAWS increased significantly (p-value < 0.05) from T1 to T5, T1 to T10 and T1 to T15. This highest PSD was related to the elbow-joint angle at 108° to 110°. The similar finding has also been reported by Chowdhury and Nimbarte. They observed the significant increase of PSD in the frequency band of 23–46 Hz and 46–93 Hz [17]. Figure 7, Fig. 8, Fig. 9 and Fig. 10, obviously, show that the position of the elbow joint affects the PSD. On the contrary, Doheny et al. reported

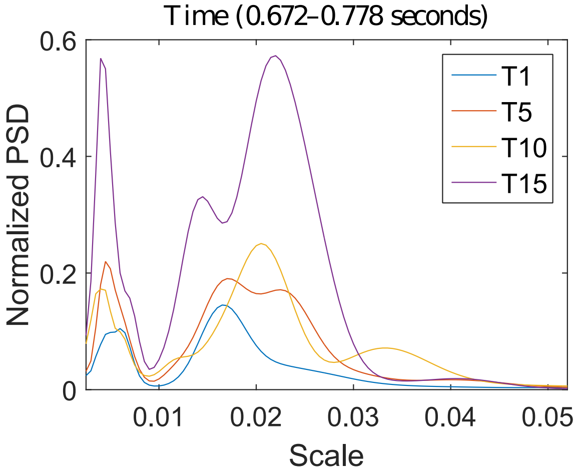


Fig. 7: The TAWS for the time range of 0.672–0.778 seconds.

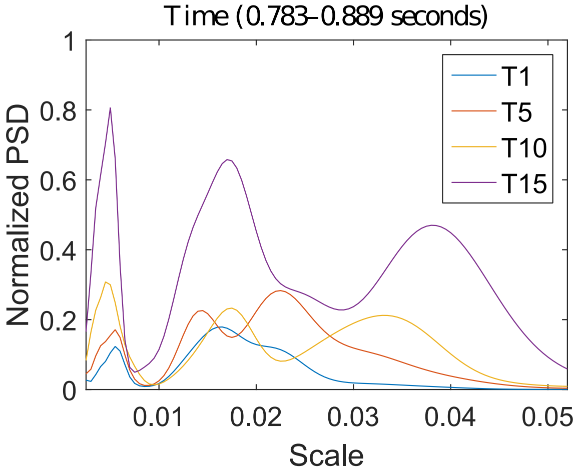


Fig. 8: The TAWS for the time range of 0.783–0.889 seconds.

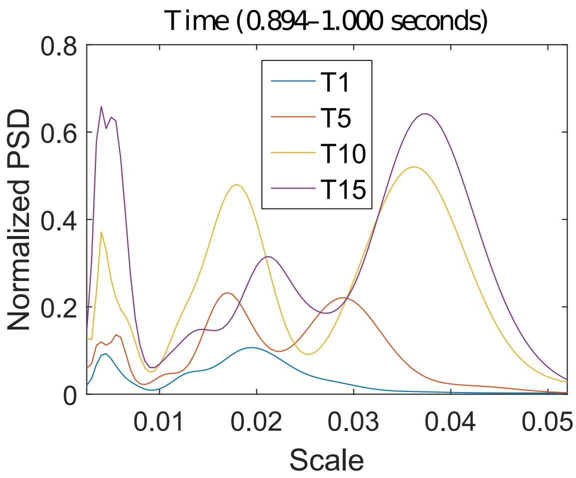


Fig. 9: The TAWS for the time range of 0.894–1 seconds.

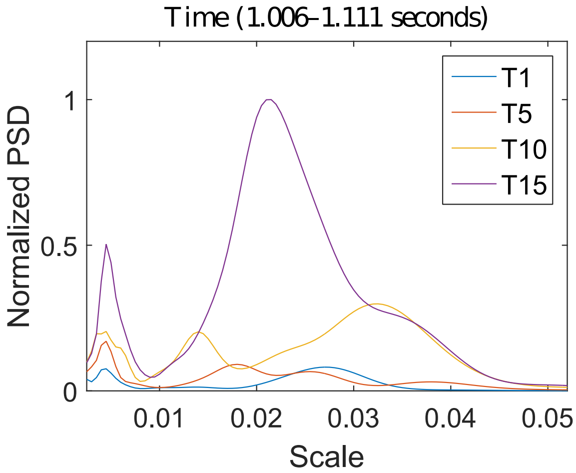


Fig. 10: The TAWS for the time range of 1.006–1.111 seconds.

that there was no relationship between the elbow joint angle and power or EMG amplitude [3]. This difference was due to the different technique in analyzing the EMG signals. They observed the relationship between the elbow joint angle and EMG amplitude using the amplitude-based parameters.

4.2. Scale-Averaged Wavelet Power

The Scale-Averaged Wavelet Power (SAWP) feature is calculated using Eq. (4). SAWP is used to test the fluctuation of PSD in the time series for specific frequency bands. By using this feature, the dominant PSD can be found in the specific time and elbow joint angle. In order to perform this calculation, the frequency was divided into ten frequency bands including 1st band (19.4–20.95 Hz), 2nd band (21.17–23.42 Hz), 3rd band (23.7–26.54 Hz), 4th band (26.9–30.62 Hz), 5th band (31.10–36.19 Hz), 6th band (36.86–44.23 Hz), 7th band (45.24–56.87 Hz), 8th band (58.54–79.62 Hz), 9th band (82.9–132 Hz) and 10th band (142–497 Hz).

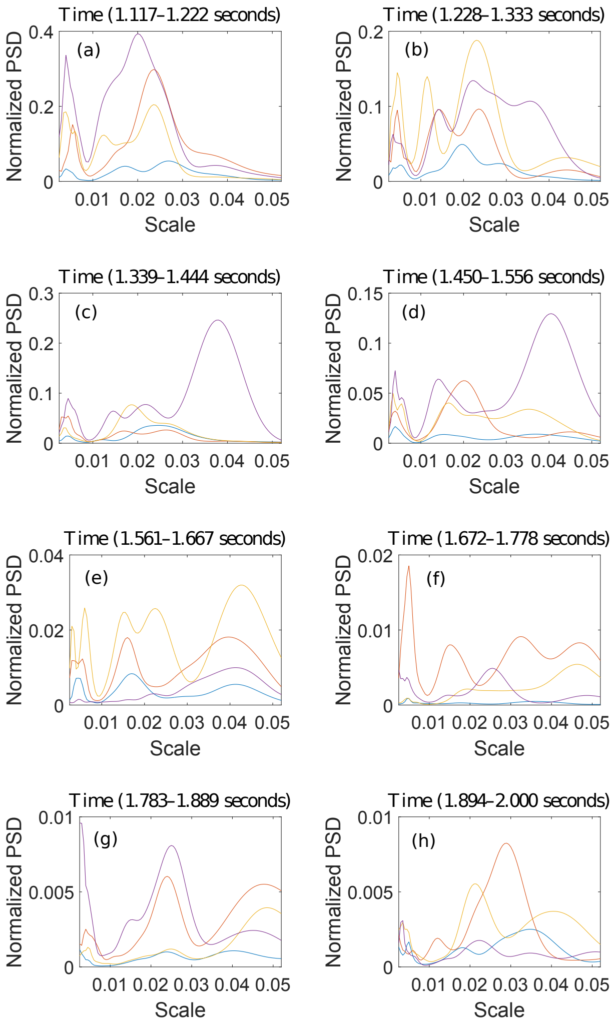
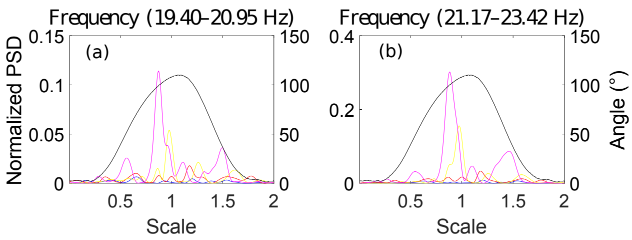
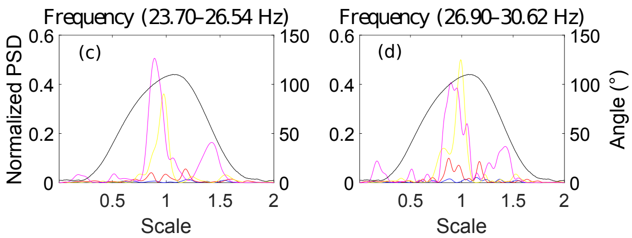


Fig. 11: The TAWS for the time range of 1.117–2 seconds.



(a) 19.4–20.95 Hz. (b) 21.17–23.42 Hz.



(c) 23.7–26.54 Hz. (d) 26.9–30.62 Hz.

Fig. 12: The SAWP for the frequency band.

Figure 12, Fig. 13, Fig. 14, Fig. 15 and Fig. 17 show that the SAWP with the maximum PSD, in the fatigue condition (T15), was mostly found in the flexion motion at the time range of 0.8 to 1.03 seconds (at the

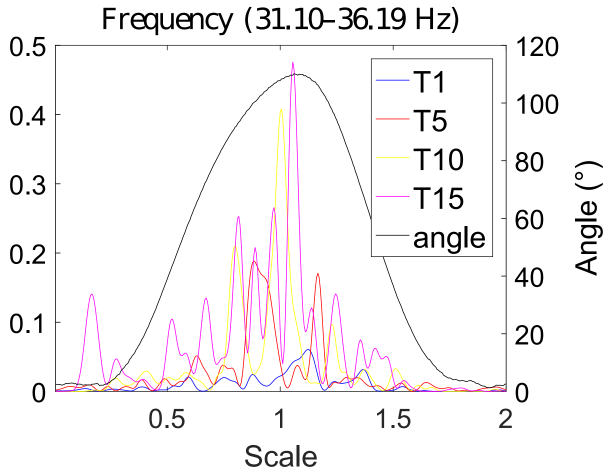


Fig. 13: The SAWP for the frequency band of 31.10–36.19 Hz.

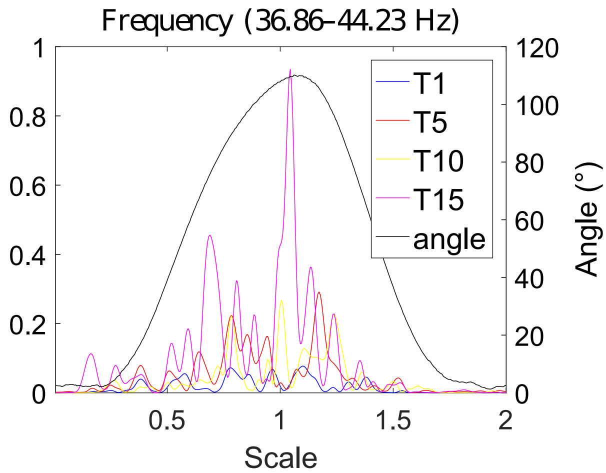


Fig. 14: The SAWP for the frequency band of 36.86–44.23 Hz.

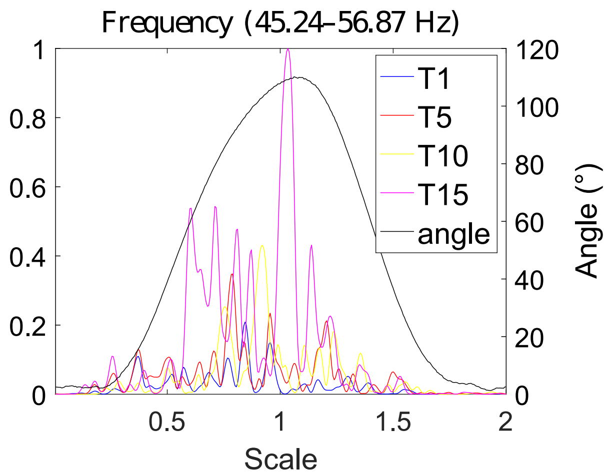


Fig. 15: The SAWP for the frequency band of 45.24–56.87 Hz.

angle of 97°–110°). Figure 16 shows that the PSD of the SAWP, in the fatigue condition, were found at several locations from 0.6 to 1.2 seconds. In this case, we could not use this band (58.54–79.62 Hz) to localize the muscle fatigue in the certain time and angle.

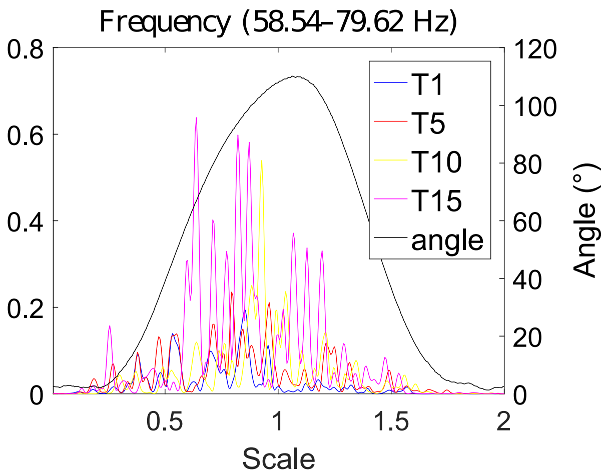
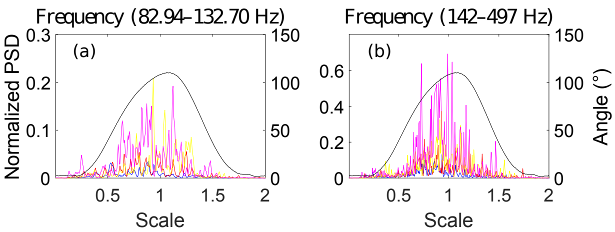


Fig. 16: The SAWP for the frequency band of 58.54–79.62 Hz.



(a) 82.9–132 Hz. (b) 142–497 Hz.

Fig. 17: The SAWP for the frequency band.

As shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16 and Fig. 17, each frequency band has different SAWP. The reliable frequency band, that could be effectively used to detect the muscle fatigue, was determined using the determination coefficient (R^2) of linear regression calculated from the average of SAWP for all the time. The linear regressions parameters (Slope, R^2, and Intercept) were calculated using the average of the SAWP for T1, T5, T10, and T15. In the frequency band of 31.10–36.19 Hz, the R^2 shows the highest value (0.979), see Tab. 1. The positive value in the R^2 indicated that the PSD magnitude increased linearly by the time. These results are similar to Karthick and Ramakrishnan's finding [6]. In their study, they used the IMNP to observe the effect of the muscle fatigue and obtained $R^2 = 0.57$ and slope $= 0.0039$ mV^2· Hz^{-1}. The increase of the PSD magnitude in this band was also similar to Chowdury and Nimbrate's finding. They found that in the frequency range of 23–46 Hz and 46–93 Hz, the magnitude of the power spectrum increased significantly.

Tab. 1: The summary of linear regression parameters for all the frequency bands.

Frequency Band (Hz)	R^2	Slope (mV^2·Hz^{-1})	Intercept (mV^2·Hz^{-1})
19.40–20.95	0.919	0.0020	0.0016
21.17–23.42	0.876	0.0058	0.0066
23.70–26.54	0.910	0.0116	0.0139
26.90–30.62	0.964	0.0123	0.0127
31.10–36.19	0.979	0.0095	0.0048
36.86–44.23	0.783	0.0135	0.0056
45.24–56.87	0.815	0.0169	0.0076
58.54–79.62	0.864	0.0106	0.0020
82.90–132.0	0.975	0.0039	0.0016
142.0–497.0	0.948	0.0111	0.0053

5. Conclusion

This study investigated the effect of muscle fatigue quantitatively on the spectral and time-frequency parameters of the EMG signal using CWT. It was found that when the muscle was in the fatigue condition, the spectral parameters of the EMG signal changed. The average of the IMNF decreased by 15.69 % and the average of the IMNP increased by 84.14 %. The optimum fatigue detection was located at the time range of 1.006 to 1.111 seconds related to the elbow joint angle in the range of 108° to 110°. These findings suggest that the CWT analysis with SAWP and TAWS features can determine the specific frequency range, time location, and elbow joint angle that is most affected when the muscle is in fatigue condition.

References

[1] BASMAJIAN, J. V. and C. J. DE LUCA. Muscle Fatigue and Time-Dependent Parameters of the Surface EMG Signal. In: *Muscles alive: their functions revealed by electromyography*. Baltimore: Williams & Wilkins, 1985, pp. 201–222. ISBN 04-716-7580-6.

[2] MERLETTI, R. and P. PARKER. *Electromyography: Physiology, Engineering, and Non-Invasive Applications*. Hoboken, NJ: John Wiley & Sons, Inc., 2004. ISBN 0-471-67580-6.

[3] DOHENY, E. P., M. M. LOWERY, D. P. FITZ PATRICK and M. J. O'MALLEY. Effect of elbow joint angle on force-EMG relationships in human elbow flexor and extensor muscles. *Journal of Electromyography and Kinesiology*. 2008, vol. 18, no. 5, pp. 760–770. ISSN 1050-6411. DOI: 10.1016/j.jelekin.2007.03.006.

[4] GONZALEZ-IZAL, M., A. MALANDA, I. N. AMEZQUETA, E. M. GOROSTIAGA, F. MALLOR, J. IBANEZ and M. IZQUIERDO.

EMG spectral indices and muscle power fatigue during dynamic contractions. *Journal of Electromyography and Kinesiology*. 2010, vol. 20, no. 2, pp. 233–240. ISSN 1050-6411. DOI: 10.1016/j.jelekin.2009.03.011.

[5] CHOWDHURY, S. K., A. D. NIMBARTE, M. JARIDI and R. C. CREESE. Discrete wavelet transform analysis of surface electromyography for the fatigue assessment of neck and shoulder muscles. *Journal of Electromyography and Kinesiology*. 2013, vol. 23, no. 5, pp. 995–1003. ISSN 1050-6411. DOI: 10.1016/j.jelekin.2013.05.001.

[6] KARTHICK, P. A. and S. RAMAKRISHNAN. Surface electromyography based muscle fatigue progression analysis using modified B distribution time-frequency features. *Biomedical Signal Processing and Control*. 2016, vol. 26, iss. 1, pp. 42–51. ISSN 1746-8108. DOI: 10.1016/j.bspc.2015.12.007.

[7] TRIWIYANTO, O. WAHYUNGGORO, H. A. NUGROHO and HERIANTO. DWT Analysis of sEMG for Muscle Fatigue Assessment of Dynamic Motion Flexion-Extension of Elbow Joint. In: *8th International Conference on Information Technology and Electrical Engineering (ICITEE)*. Yogyakarta: IEEE, 2016, pp. 1–6. ISBN 97-815-0904-139-8. DOI: 10.1109/ICITEED.2016.7863300.

[8] ADDISON, P. S. *The Illustrated Wavelet Transform Handbook: Introductory Theory and Applications in Science, Engineering, Medicine and Finance*. New York: Taylor & Francis, 2002. ISBN 97-807-5030-692-8.

[9] TORRENCE, C. and G. P. COMPO. A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society*. 1998, vol. 79, no. 1, pp. 61–78. ISSN 1520-0477. DOI: 10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

[10] DE LUCA, G. Fundamental Concepts in EMG Signal Acquisition. In: *Delsys* [online]. 2003, pp. 1–31. Available at: http://delsys.com/Attachments_pdf.

[11] ROGERS, D. R. and D. T. MACISAAC. EMG-based muscle fatigue assessment during dynamic contractions using principal component analysis. *Journal of Electromyography and Kinesiology*. 2011, vol. 21, no. 5. pp. 811–818. ISSN 1873-5711. DOI: 10.1016/j.jelekin.2011.05.002.

[12] WINSLOW, J., P. L. JACOBS and D. TEPAVAC. Fatigue compensation during FES using surface EMG. *Journal of Electromyography and Kinesiology*. 2003, vol. 6, no. 6, pp. 555–568. ISSN 1050-6411. DOI: 10.1016/S1050-6411(03)00055-5.

[13] TAN, L. and J. JIANG. *Digital Signal Processing: Fundamental and Applications*. Boston: Academic Press. ISBN 978-0123740908.

[14] LEAO, R. N. and J. A. BURNE. Continuous wavelet transform in the evaluation of stretch reflex responses from surface EMG. *Journal of Neuroscience Methods*. 2004, vol. 133, no. 1–2, pp. 115–125. ISSN 0165-0270. DOI: 10.1016/j.jneumeth.2003.10.003.

[15] BASTIAENSEN, Y., T. SCHAEPS and J. P. BAEYENS. Analyzing an sEMG signal using wavelets. In: *4th European Conference of the International Federation for Medical and Biological Engineering*. Berlin: Springer, 2008, pp. 156–159. ISBN 978-35-4089-207-6. DOI: 10.1007/978-3-540-89208-3_39.

[16] DE MICHELE, G., S. SELLO, M. C. CARBONCINI, B. ROSSI and S. K. STRAMBI. Cross-correlation time-frequency analysis for multiple EMG signals in Parkinson's disease: A wavelet approach. *Medical Engineering & Physics*. 2003, vol. 25, no. 5, pp. 361–369. ISSN 1350-4533. DOI: 10.1016/S1350-4533(03)00034-1.

[17] CHOWDHURY, S. K. and A. D. NIMBARTE. Comparison of Fourier and Wavelet Analysis for Fatigue Assessment During Repetitive Dynamic Exertion. *Journal of Electromyography and Kinesiology*. 2015, vol. 25, no. 2. pp. 5–13. ISSN 1050-6411. DOI: 10.1016/j.jelekin.2014.11.005.

About Authors

TRIWIYANTO was born in Surabaya, Indonesia. He received his M.Sc. degree in Electronic Engineering in Institute of Technology Sepuluh Nopember in 2004, Surabaya, Indonesia. He is currently a Ph.D. candidate in Electrical Engineering at Gadjah Mada University, Yogyakarta, Indonesia. His research interests include biomedical signal analysis, embedded system, electronic instrumentation, assistive and rehabilitation devices.

Oyas WAHYUNGGORO was born in Jogjakarta, Indonesia. He received his Ph.D. degree in Electrical and Electronic Engineering from the Universiti Teknologi Petronas, Malaysia in 2011. His research interests include biomedical signal processing, intelligent system, and control system.

Hanung ADI NUGROHO was born in Jogjakarta, Indonesia. He received his Ph.D. degree in Electrical and Electronic Engineering from the Universiti Teknologi Petronas, Malaysia in 2012. His research interests include biomedical signal processing and image processing.

HERIANTO was born in Jogjakarta, Indonesia. He received his D.Eng. in the Department of Mechanical and Control Engineering, Tokyo Institute of Technology, Japan, in 2009. His research interests include robotics and manufacture. His current research is product design and development especially in rehabilitation robot.