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Endurance Capacity of the Biceps Brachii Muscle Using the High-to-Low Ratio between Two Signal Spectral Moments of Surface EMG Signals during Isotonic Contractions

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Abstract – Many researchers had examined the validity of using the high-to-low ratio between two fixed frequency band amplitudes (H/L-FFB) from the surface electromyography of a face and body as the first spectral index to assess muscle fatigue. Despite these studies, the disadvantage of this index is the lack of a criterion for choosing the optimal border frequency. We tested the potential of using the high-to-low ratio between two signal spectral moments (H/L-SSM), without fixed border frequencies, to evaluate muscle fatigue and predict endurance time (T_{end}), which was determined when the subject was exhausted and could no longer follow the fixed contraction cycle. Ten healthy participants performed five sets of voluntary isotonic contractions until they could only produce 10% and 20% of their maximum voluntary contraction (MVC). The T_{end} values for all participants were 138 ± 35 s at 10% MVC and 69 ± 20 s at 20% MVC. Changes in conventional spectral indices, such as the mean power frequency (MPF), Dimitrov spectral index (DSI), H/L-FFB, and H/L-SSM, were extracted from surface EMG signals and were monitored using the initial slope computed every 10% of T_{end} as a statistical indicator and compared as a predictor of T_{end}. Significant correlations were found between T_{end} and the initial H/L-SSM slope as computed over 30% of T_{end}. In conclusion, initial H/L-SSM slope can be used to describe changes in the spectral content of surface EMG signals and can be employed as a good predictor of T_{end} compared to that of conventional spectral indices.

Keywords: Electromyography, Signal spectral moment, High-to-low ratio, Isotonic contractions, Endurance time (T_{end})

1. Introduction

The capacity to maintain a given force over time, i.e., the capacity to endure a specific motor task, is an important determinant of muscle performance and resistance to fatigue [1, 2, 3, 4]. Methods that allow reliable estimates of muscle endurance capacity during dynamic exercise are of great importance for studying muscle function and motor control because most actions and movements in daily life involve dynamic muscle contraction, such as those used for sporting activities and clinical practice of a face and body.

Spectral compression of surface electromyography (sEMG) signals towards lower frequencies during static or dynamic contraction is related to slowing of muscle fiber propagation velocity [5, 6]. As the first spectral index, the high-to-low ratio between power content in high and low fixed frequency bands (H/L-FFB) is related to spectral compression of sEMG signals. Moxham et al [7] used this ratio between high (130-238 Hz) and low (20-40 Hz) frequency-band amplitudes. Other high and low bandwidth border frequencies have been used [8-10]. However, reliable methods to choose the optimal border frequency are limited [11-13] proposed to use changes in mean power frequency (MPF) which means the high-to-low ratio between an order 1 and an order 0 spectral moment as a measure of the change in muscle fiber propagation velocity. Stulen and De Luca [14] also proposed using changes in median frequency (MDF), which is less sensitive to noise.

Many researchers have attempted to develop a method for estimating muscle fatigue and endurance time (T_{end}) using spectral indices, such as MDF and MPF, from sEMG [4, 9, 15-17]. However, Chesler and Durfee [18] found that these indices were unreliable for predicting and tracking muscle fatigue because they are not useful for noninvasively estimating changes in muscle fiber propagation velocity due to their sensitivity [11, 12].

Dimitrov et al [19] attempted to develop a reliable method to assess muscle fatigue from sEMG signals during dynamic fatiguing tasks by developing the Dimitrov

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Spectral Index (DSI) which means the low-to-high ratio between an order (-1) and an order 5 spectral moment without choosing the fixed border frequencies. Although the DSI shows a more notable change in muscle fatigue than that of MDF or MPF, González-Izal et al [20] employed a logarithmic transformation of DSI as a predictor of the performance change in muscle power to reduce the large variability in the DSI change. Therefore, we present the high-to-low ratio between order 5 and order (−1) signal spectral moments (H/L-SSM) which emphasizes the high and low frequency amplitudes and thus decreases throughout repeated submaximal contractions. To our knowledge, predicting T_{end} using changes in H/L-SSM at submaximal time periods shorter than the T_{end} during isotonic contractions has not been reported.

Our study was designed to test whether changes in H/LSSM, calculated over a shorter duration than total endurance, could predict endurance capacity of the biceps brachii muscle. Thus, the changes in this index were calculated and compared with conventional spectral indices, including MPF, DSI, and H/L-FFB. Subsequently, the relationships between T_{end} and the initial slopes of the spectral indices were analyzed as predictors of T_{end}.

2. Methods

2.1 Participants

Ten healthy volunteers (5 women, 5 men), with no previous motor disorders or current injuries, participated in this experiment. All participants were right-handed, and their general characteristics (age: 27.4 ± 5 years; BMI: 23.7 ± 4 kg/m^2) were measured. The men and women were of the young age on average, but the men were heavier and taller than the women [21-23]. The participants were familiarized with the equipment and protocol before starting the trials. All procedures in this study were performed according to the Declaration of Helsinki.

2.2 Experimental procedure

Maximum voluntary contraction (MVC) forces of the participants were measured from 90° right (dominant) elbow flexion using a manual muscle tester (Lafayette Instrument, Lafayette, IN, USA). Three maximal contractions of 3 s each were performed with a 3 min rest period between contractions. The MVC was determined as the average of the three values [24].

A schematic diagram of isotonic contraction of the biceps brachii muscle is shown in Fig. 1. Participants were asked to stand erect with their upper arm fixed and to move their lower arm through a range of motion from full extension to 110° flexion at a speed of 25 repetitions per minute [10].

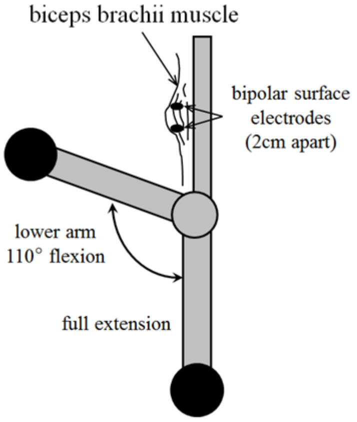


Fig. 1. Schematic diagram of an isotonic contraction of the biceps brachii muscle

Each repeated contraction was assessed by an investigator and was considered successful if performed with the full range of motion within the metronome-guided time interval (2.4 s). During one set of the isotonic contraction trials, the participants were asked to continue repetitive contractions until exhaustion. The time of termination was determined when the participant indicated that they could no longer continue full range of motion with the metronome speed for more than two repetitions, despite verbal encouragement without threatening. This time point was recorded as the T_{end} for each participant.

Ten participants completed five sets of the isotonic contraction trials until exhaustion at 10% MVC and 20% MVC, respectively. Two hours of rest was provided between three sets of trials conducted over 1 day, and the subsequent two sets of trials were conducted after 3-7 days to avoid fatigue [15]. Surface EMG signals obtained from the biceps brachii using bipolar surface electrodes (2 cm apart) [25], which were connected to a measuring apparatus (ME 6000, Mega Electronics Ltd, Kuopio, Finland). The electrodes were secured to the skin with anti-allergic tape after the skin was cleaned with alcohol, and placed on the area of greatest muscle bulk along the longitudinal midline of the muscle [26].

2.3 Signal analysis and statistics

Surface EMG signals obtained from the biceps brachii were recorded on a host PC at a sampling rate of 1 kHz with 16-bit resolution, and a notch filter was used to remove the main frequency at 60 Hz. All signals were segmented consecutively using a 4-s time Hamming window every 0.2 s. And a short-time Fourier transformation was conducted on each windowed segment to estimate the power spectrum. This power spectrum was used to calculate spectral indices, such as MPF [13], DSI [19], H/L-FFB which is the high-to-low ratio with two fixed frequency bandwidths of high (400-500 Hz) and low (15-45 Hz) frequency [10, 27], and H/L-SSM which is the high-to-low ratio between the order 5 and the order (−1) signal spectral moment which emphasizes the high and low frequency amplitudes, respectively.

T_{end} (endurance time) of each participant during the isotonic trials was divided into 10 equal intervals at every 10% of T_{end} [17, 27]. An interpolated value was calculated from the nearest sampled value when there was no measurement at a resampling point. Changes in these spectral indices were expressed using a curve fitting statistical model: the initial slope of the linear regression model from the onset to every 10% of T_{end}, such as the MPF slope, the DSI slope, the H/L-FFB slope, and the H/LSSM slope.

Paired t-tests were conducted to evaluate significant differences between the initial slopes of the spectral indices [15]. Pearson's correlation coefficient (R value) was calculated between T_{end} and initial slope at every 10% of T_{end} to quantify predictive ability. The coefficient of variation (CV) was used to do quality assurance method. In this study, CV was calculated from the initial slopes and the R-values. The level of statistical significance was set at $p < 0.05$ [9, 17].

3. Results

Individual T_{end} values were 138 ± 35s at 10% MVC contraction level and 49 ± 20s at 20% MVC contraction level. This result indicates that the T_{end} values at the two contraction levels were different, and significant correlations were observed between T_{end} and contraction level ($p < 0.05$).

MPF decreased linearly with time at 10% and 20% MVC contraction level during the isotonic fatigue trial and ended at 86.2 ± 8.5% and 81.6 ± 5.5% respectively. Total mean MPF slopes from onset to every 10% of T_{end} were −0.16% · s−1 and −0.44% · s−1, respectively (Fig. 2), whereas DSI increased and reached 330.7 ± 177.9% and 327.8 ± 83.9%. The means of the DSI slopes were 2.4% · s−1 and 5.7% · s−1, respectively (Fig. 3). These results show that DSI changes more notable in muscle fatigue than that of MPF.

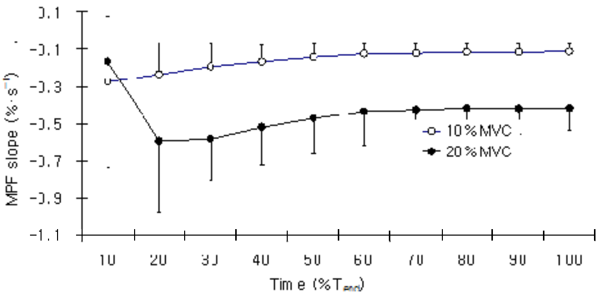


Fig. 2. Mean initial changes in the slopes of mean power frequency (MPF) during isotonic fatiguing contractions at 10% MVC (white circles) and 20% MVC (black circles)

In contrast to DSI, H/L-FFB and H/L-SSM decreased more rapidly than that of MPF. H/L-FFB reached 16.7 ± 24.4% and 13.4 ± 13.0% at the 10% and 20% MVC, and means of the H/L-FFB slopes were −1.0% · s−1 and −2.7% · s−1, respectively (Fig. 4). H/L-SSM reached 28.0 ± 22.0% and 23.0 ± 12.4%, and total H/L-SSM slope means were −0.9% · s−1 and −2.3% · s−1, respectively (Fig. 5). Paired t-tests were used to compare MPF slopes with H/LFFB, and H/L-SSM, and significant differences

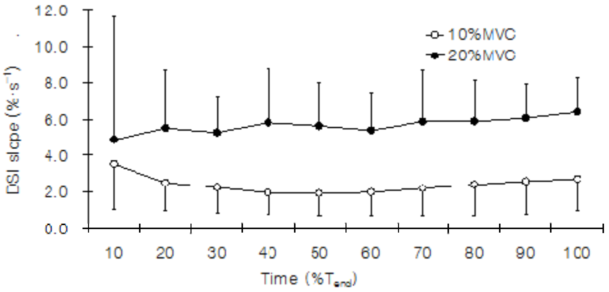


Fig. 3. Mean initial changes in the slopes of mean power frequency (MPF) during isotonic fatiguing contractions at 10% MVC (white circles) and 20% MVC (black circles)

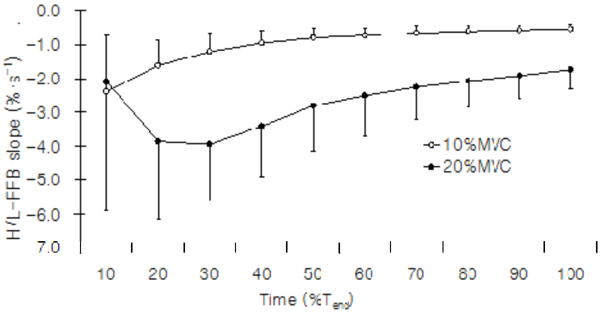


Fig. 4. Mean initial changes in slopes of the high-to-low ratio between two fixed frequency bank amplitudes (H/L-FFB) during isotonic fatiguing contractions at 10% MVC (white circles) and 20% MVC (black circles)

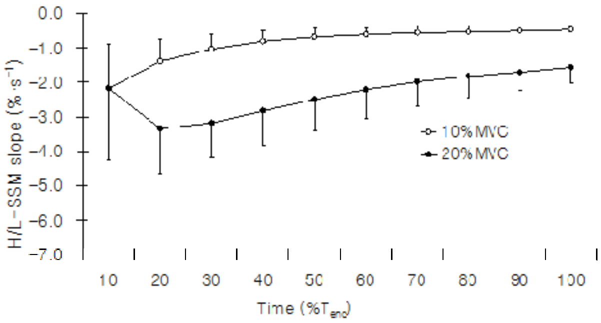


Fig. 5. Mean initial changes in slopes of the high-to-low ratio between two signal spectral moments (H/L-SSM) during isotonic fatiguing contractions at 10% MVC (white circles) and 20% MVC (black circles)

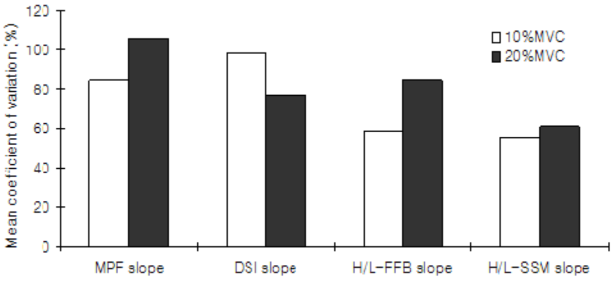
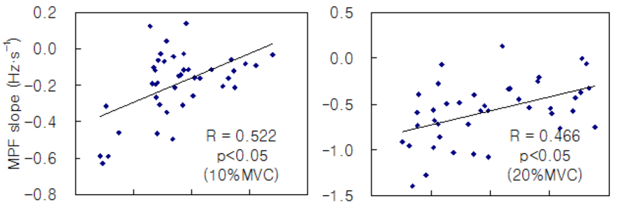
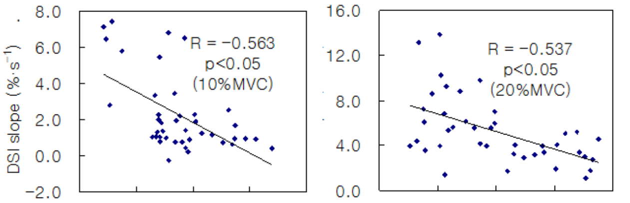


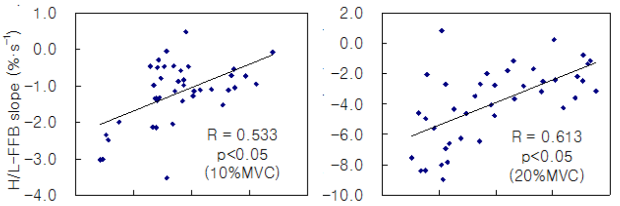
Fig. 6. Mean values of coefficients of variation for the initial slopes of the four spectral indices



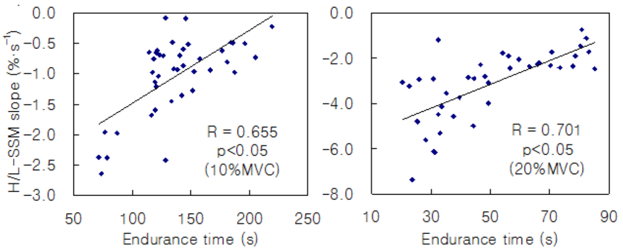
(a) Mean power frequency (MPF) slope as estimated over 30% of endurance time (T_{end}) at 10% MVC (left) and 20% MVC (right)



(b) Dimitrov spectral index (DSI) slope as estimated over 30% of endurance time (T_{end}) at 10% MVC (left) and 20% MVC (right)



(c) Fixed frequency band amplitude (H/L-FFB) slope as estimated over 30% of endurance time (T_{end}) at 10% MVC (left) and 20% MVC (right)



(d) The two signal spectral moment (H/L-SSM) slope as estimated over 30% of endurance time (T_{end}) at 10% MVC (left) and 20% MVC (right)

Fig. 7. Scatter plots of the relationship between the initial slopes of the four spectral indices with respect to 30% of endurance time (T_{end}) vs. T_{end} for all participants at 10% MVC (left) and 10% MVC (right)

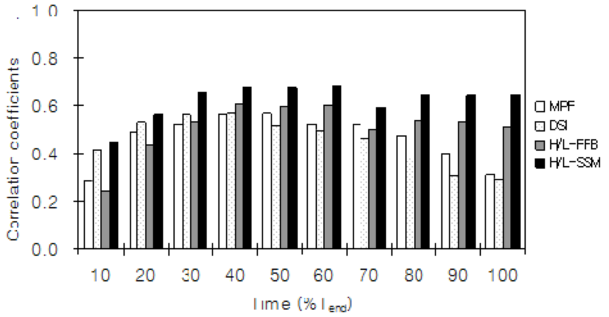


Fig. 8. Correlation coefficients at 10% MVC between the initial slopes of mean power frequency (MPF) (white bars), Dimitrov spectral index (DSI) (dotted bars), fixed frequency band amplitude (H/L-FFB) (gray bars) and two signal spectral moment (H/L-SSM) (black bars), and the endurance times (T_{end}) for all participants

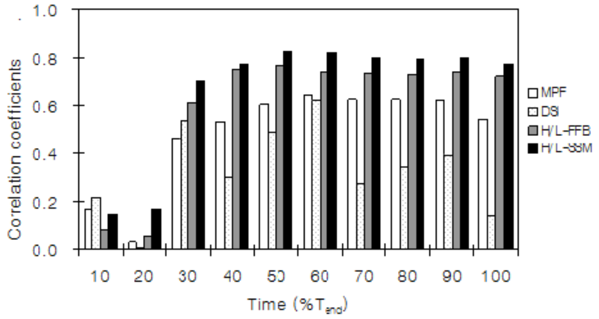


Fig. 9. Correlation coefficients at 20% MVC between the initial slopes of mean power frequency (MPF) (white bars), Dimitrov spectral index (DSI) (dotted bars), fixed frequency band amplitude (H/L-FFB) (gray bars), and two signal spectral moment (H/L-SSM) (black bars) with the endurance times (T_{end}) for all participants

were observed at both contraction levels ($p < 0.05$). But the H/LFFB slope was not significantly different from that of H/LSSM. Mean values of CV for the initial MPF, DSI, H/LFFB, and H/L-SSM slopes are given in Fig. 6. The H/LSSM slope had the least relative variation.

To show the relationships between T_{end} and the initial slopes of the four spectral indices as estimated over 30% T_{end}, the scatterplots and regression lines are shown in Fig. 7. Figs. 8 and 9 showed the R values between these four slopes and T_{end} with respect to every 10% of T_{end}.

In addition, Table 1 showed CV to demonstrate R values from 30% to 100% of T_{end}. The means of R values from MPF, DSI and H/L-FFB were less than 0.55 ($CV \geq 7.76$) at 10% MVC and 0.72 ($CV \geq 6.60$) at 20% MVC. However, the mean from H/L-SSM was 0.65 ($CV=4.54$) at 10% MVC and 0.79 ($CV=4.96$) at 20% MVC.

These results showed that the H/L-SSM slope after 30% of T_{end} had a higher correlation and a lower CV than those of the conventional indices at both contraction levels. Therefore, the most reliable predictor of T_{end} compared with the initial slopes of the conventional spectral indices was those of H/L-SSM at both contraction levels.

4. Discussion

The main aim of our study was to test the utility of short duration isotonic contractions of the biceps brachii muscle for predicting endurance time using the H/L-SSM without fixed border frequencies. Thus, the relationships between T_{end} and the initial slopes described by the linear regression analysis estimated over every 10% of T_{end} were evaluated.

4.1 Signal processing

The sEMG signals may have been be non-stationary during dynamic contractions for the endurance test; thus, several factors, such as a change in the number of active motor units, changes in force through range of motion, and changes in fiber and muscle length, together with a change in muscle fiber conduction velocity due to muscle fatigue [2, 6, 28-30], may also increase. Although these factors could not be entirely excluded and may have affected the estimated spectral indices, the careful placement of the electrodes between the innervation zone and the tendon and the normalized amplitudes should have minimized the influence on the results [26, 31]. Discrete wavelet transformation [32] and logarithmic transformation [20] were used to extract the muscle fatigue spectral indices during the endurance test dynamic contractions to minimize the effects of these factors. However, MacIsaac et al. [33] demonstrated that muscle fatigue can be assessed during dynamic contractions using a traditional short-term Fourier transformation. Some authors [19, 31] have extracted the signal spectral moments of spectral indices using Fourier transformation. Coorevits et al. [34] found that the continuous wavelet transformation and traditional Fourier transformation are generally reliable to assess muscle fatigue.

4.2 Predictability

The sEMG signals may have In agreement with previous studies, the dynamic fatiguing exercise led to major muscle fatigue, as there was a shift in the EMG power spectrum to lower amplitude and frequency components [32]. The results for the initial MPF, DSI, H/L-FFB, and H/L-SSM slopes during isotonic contraction (Fig. 2-5) agreed with those obtained by Maïsetti et al [9], Lee et al [10], and Dimitrov et al [19]. As H/L-SSM was calculated using the order 5 and order (−1) signal spectral moments, the qualitative changes in H/L-SSM for muscle fatigue across repetitive contractions reflected those of the EMG spectral frequency characteristic, such as MPF and DSI [19, 31, 35, 36], and the changes in the initial slopes varied among subjects with respect to time [24, 27, 35]. In contrast, the coefficient of variation (CV) of H/L-SSM slope, without a fixed frequency band, shows a less variability than those of the conventional spectral indices (Fig. 6). Thus, we found that H/L-SSM slope had higher correlation coefficients with T_{end} than that of conventional spectral indices. This relationship was less at 10% MVC (Fig. 8) than that at 20% MVC (Fig. 9); Christensen et al [37] demonstrated that spectral indices at 9-10% MVC may be unsuitable for assessing muscle fatigue during static and dynamic contractions.

Van Dieën et al [15] demonstrated that endurance time predictions from shorter periods than 50% of T_{end} were unreliable. However, Table 1 showed that CV of R values from H/L-SSM slope was less than those from the conventional spectral indices. These results meant that the concentration of R values from H/L-SSM slope after 30% of T_{end} was higher than those from the others.

Our major findings reveal that the H/L-SSM slope, as estimated over 30% of T_{end} and with no criterion to choose the optimal border frequencies for the high and low frequency bands, was significantly related with T_{end}, and thus was a suitable method for monitoring biceps brachii fatigue and for predicting T_{end}.

5. Conclusion

The initial H/L-SSM slopes were used as predictors of endurance time during the endurance test isotonic contractions, without choosing the optimal border frequencies, which were estimated every 10% of the T_{end} and their relationships with T_{end} were compared with those of conventional spectral indices. The results show that the initial slope of the H/L-SSM spectral ratio, as estimated over 30% of the T_{end} shorter than the first half, was significantly related with T_{end}. The results demonstrate that H/L-SSM could be a suitable spectral index for monitoring biceps brachii muscle fatigue and to estimate endurance capacity without continuing isotonic contractions until exhaustion.

Acknowledgements

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