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ORIGINAL ARTICLE

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Spectral moments of mechanomyographic signals recorded with accelerometer and microphone during sustained fatiguing contractions

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Abstract The aim of this study was to analyse the trends of the first three power spectral moments of the mechanomyogram (MMG) signal recorded by a microphone (MMG_{MIC}) and an accelerometer (MMG_{ACC}) during sustained contractions. MMG signals were recorded from the biceps brachii muscle in 14 healthy male subjects during a 3 min isometric elbow flexion at 30% of the maximal voluntary contraction. MMG absolute and normalised root mean square (RMS), mean power frequency (MNF), power spectral variance (Mc_2), and skewness (μ_3) were computed. For both MMG_{MIC} and MMG_{ACC}, absolute and normalised RMS and Mc_2 increased while MNF and μ_3 decreased with contraction time ($P < 0.001$). The rates of change of RMS over time were significantly correlated ($P < 0.001$) for MMG_{MIC} and MMG_{ACC} but not correlated for spectral moments. The coefficient of variation of RMS was higher for MMG_{MIC} than for MMG_{ACC}, while the opposite was observed for μ_3 ($P < 0.05$). It was concluded that higher order spectral moments of the MMG signal change during sustained contraction, indicating a complex modification of the shape of the power spectrum and not just scaling of the bandwidth. This is most likely due to the additional motor unit recruitment with fatigue and to the non-linear summation of motor unit contributions to the signal. Moreover, the characteristics of MMG signals recorded with microphones and accelerometers have important differences, which should be taken into account when comparing results from different studies.

Keywords Spectral moments · Microphone · Accelerometer

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1 Introduction

Slow bulk movement of the muscle, excitation into ringing of the muscle at its own resonance frequency [1, 5], and pressure waves due to the dimensional changes of the active muscle fibres [15] generate oscillations recorded as the mechanomyogram (MMG) signal. MMG has been used to study the mechanical activity of a contracting muscle and may reflect motor unit recruitment, discharge rate, synchronisation and, to some extent, factors which affect the muscle physical milieu, such as intra-muscular pressure, stiffness, and osmotic pressure [15, 16].

Over the last two decades, several types of transducers have been applied to detect MMG signals, including piezoelectric contact sensor, microphones, accelerometers, and laser distance sensors. Piezoelectric contact sensors are not commonly used since their weight and the applied pressure to obtain a mechanical coupling damp the recorded MMG signal [16]. Condenser microphones acting as a displacement meter are more often applied but, as the piezoelectric contact sensors, they require a coupling, for example, air, gel between the muscle and the microphone [21]. The volume of the air chamber influences the amplitude and the frequency content of the recorded MMG signal [21]. Accelerometers, reflecting the acceleration of body surface vibration, are currently the most applied sensors for MMG recording due to their small weight and size, easy attachment, and high reliability [22]. Recently, laser displacement sensors have also been used since it is possible to study muscle dimensional changes without additional inertial load [16, 19]. However, accelerometers weighting less than 5 g do not interfere with muscle surface dynamics and provide accurate MMG recordings [22]. Due to different transduction modes inherent to the various sensors, MMG signals have different temporal and frequency characteristics [21]. However, there are no reports comparing the features of MMG signals recorded with different sensors during sustained isometric contractions.

During sustained isometric contractions at forces above 30% of the maximum voluntary contraction (MVC), time-domain MMG signal descriptors, such as root mean square (RMS), usually increase while characteristic power spectral frequencies, for example, mean frequency (MNF), decrease [6, 9, 10, 15, 20]. The first-order spectral moment provides full description of the relative changes in the power spectrum during sustained contraction if the shape of the spectrum does not change, that is, if only a compression of the bandwidth occurs. This assumption is usually done in electromyographic recordings [13], but it is likely not valid in MMG recordings, due to the complex non-linear summation of the single motor unit contributions [18]. However, there are no studies that investigated changes in higher order spectral moments of MMG signals during sustained contractions.

Therefore, the aim of this study is to analyse the trends of the first three power spectral moments of the MMG signal recorded concomitantly by a microphone and an accelerometer during sustained contractions.

2 Methods

2.1 Subjects

Fourteen healthy male volunteers (right-handed) without any history of neuromuscular or orthopaedic diseases participated in the study (age, mean ± SD: 26.7 ± 4.9 years, body weight: 76.3 ± 9.5 kg, height: 1.80 ± 0.07 m). Informed consents were obtained from all participants. The study was conducted in conformity with the Declaration of Helsinki.

2.2 MMG signal recordings

The MMG_{MIC} signal was detected by an air-coupled condenser microphone (type BCM 9765, BeStar Acoustic, Jiangsu, China; diameter 9.7 mm, weight 18 g, 54 dB sensitivity where $1\text{Pa} = 7$ mV, linear transmission in the frequency range 0.1–5,000 Hz). The distance from the microphone to the skin surface was 9 mm. The MMG_{MIC} signal was amplified at 1–20, band-pass filtered at 1–500 Hz, sampled at 1 kHz, and converted in numerical format with a 14-bit A/D board (Analogue Devices, Norwood, MA).

MMG_{ACC} was recorded by a piezoelectric accelerometer (Bang & Olufsen Technology, Struer, Denmark; diameter 17.6 mm, weight 2.9 g, sensitivity 30 pC/m·s^{-2}, linear transmission in the frequency range of 0.1–800 Hz). The MMG_{ACC} signal was amplified (Bruel & Kjær Nexus, Nærum, Denmark) in the bandwidth 0.1–100 Hz, sampled at 1 kHz, and digitised on 12 bits (National Instrument, Austin, TX, USA).

The two MMG transducers were attached with double-sided adhesive tape over the biceps brachii muscle, adjacent with respect to each other, along the line between the acromion and the fossa cubit. The accelerometer was placed 31 mm distal to the condenser microphone in order not to cover the end plate zone or to get too close to the musculotendinous region and to measure MMG with the two transducers from the same part of the muscle relative to the innervation zone.

Prior to data analysis, MMG_{ACC} and MMG_{MIC} signals were off-line digitally band-pass filtered with bandwidth 2–100 Hz (second-order, anti-causal Butterworth filter).

2.3 General procedures

The subject sat comfortably in an upright position on a chair with his left arm along the trunk and the right forearm 90° flexed with respect to the arm. The forearm was in a neutral position (semi pronated) and supported on a table. A belt was fastened around the wrist and connected to a piezoelectric force transducer (Kistler type 9311A, Bern, Switzerland), fixed to the floor.

The subject performed three 5 s maximal voluntary isometric elbow flexions, with 2 min rest in between. The trial resulting in the highest force was considered as the MVC. After 5 min rest, the subject exerted a 3 min right elbow isometric flexion at 30% MVC (Fig. 1) corresponding to approximately 50% of the endurance time [24]. The subjective score of fatigue was indicated by the subject after the sustained contraction on a 10 cm visual analogue scale, where 0 cm indicated 'no fatigue' and 10 cm 'exhaustion'.

2.4 Data processing

The RMS value of the MMG signals from the three MVC trials was computed over 1 s epochs with 100 ms overlap. The maximum RMS value was used for normalisation. RMS, first-, second-, and third-order spectral moments were computed over non-overlapping 1 s long epochs from the MMG signals recorded during the sustained contractions. The power spectral density (Fig. 1) was computed with Welch periodogram with Hanning window and zero-padding to 1,024 samples [23]. The first-order moment (MNF) is defined as

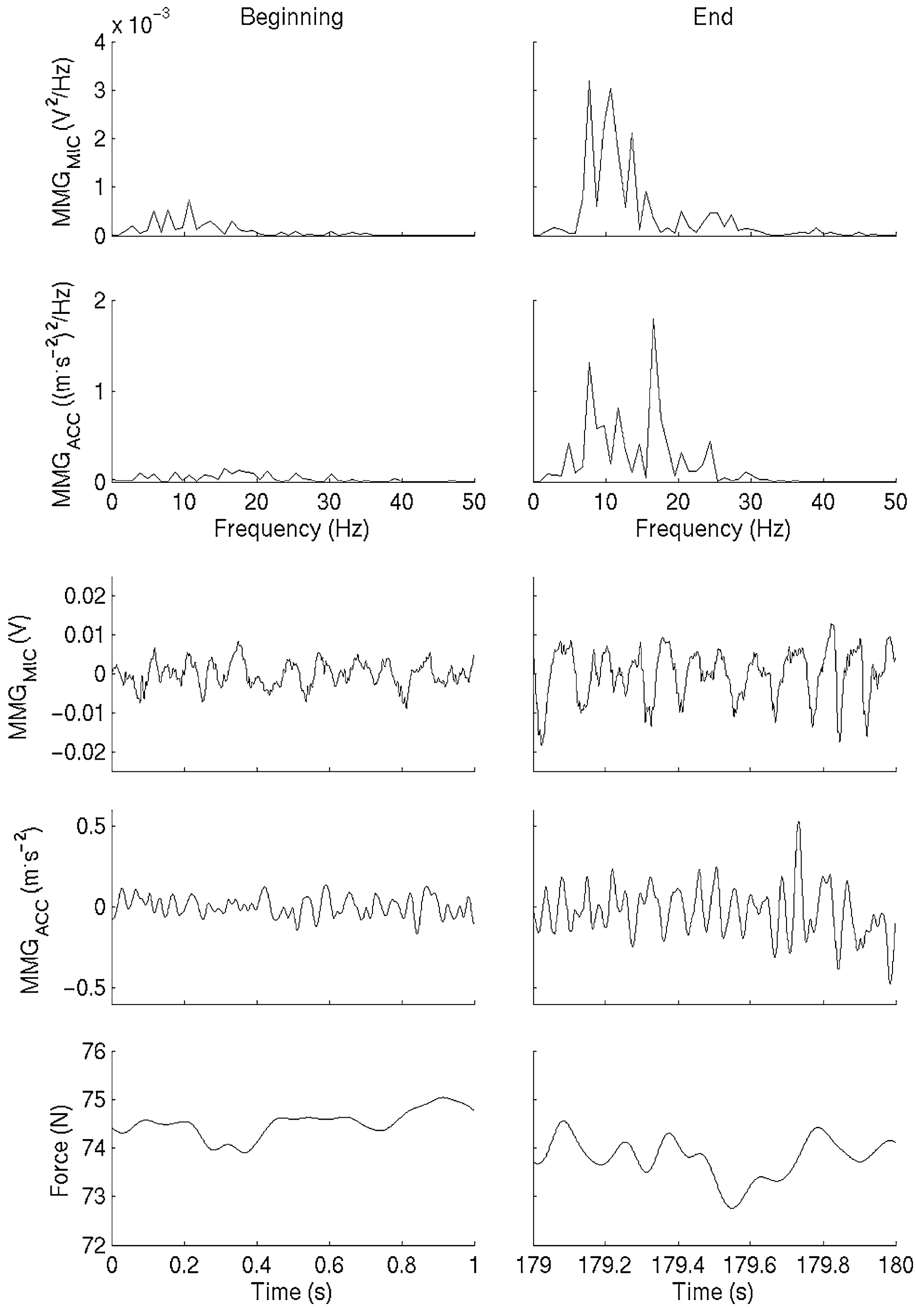


Fig. 1 Example of MMG_{MIC} and MMG_{ACC} signals and power spectral density (PSD) at the beginning and end of a 3 min sustained isometric contraction at 30% maximum voluntary contraction

$$\mathrm{MNF} = \frac{\sum_{i=1}^{+N} f_i \ \mathrm{PSD}_i}{\sum_{i=1}^{+N} \ \mathrm{PSD}_i}$$

where PSD_i is the ith line of the power spectral density and N is the highest harmonic considered.

The second-order central moment (Mc_2), that is, the variance of the power spectral density, and the normalised third central moment (μ_3), that is, the skewness, are defined as

$$\mathrm{Mc}_2 = \sum_{i=1}^{+N} (f_i - \ \mathrm{MNF})^2 \ \mathrm{PSD}_i$$

$$\mu_3 = \frac{\sum_{i=1}^{+N} (f_i - \ \mathrm{MNF})^3 \ \mathrm{PSD}_i}{\left(\sum_{i=1}^{+N} (f_i - \ \mathrm{MNF})^2 \ \mathrm{PSD}_i\right)^{3/2}}$$

Absolute RMS values and normalised (with respect to MVC) RMS values were used for further analysis. Spectral moments were analysed as absolute values and as values normalised to the initial value. To decrease variability and reduce the amount of data, mean and standard deviation of absolute and normalised RMS, MNF, Mc_2, and μ_3 values were computed over sets of 10 consecutive values (without overlapping). The coefficient of variation of RMS, MNF, Mc_2, and μ_3 values were obtained as the ratio between the standard deviation and the mean.

2.5 Statistical analysis

Two-way repeated measures analysis of variance (ANOVA) with Student-Newman-Keuls (SNK) post-hoc test for pair-wise comparisons was applied for MMG absolute and normalised RMS, MNF, Mc_2, and μ_3 values. The factors were contraction time (time) and transducer type (microphone and accelerometer). $P < 0.05$ was considered significant. Data are presented as mean and standard error (SE) of the mean.

3 Results

All subjects were able to maintain the required force level for 3 min. At the end of the contraction, the mean rating of perceived exertion was 6.4 ± 0.3 cm.

3.1 Comparison of MMG_{MIC} and MMG_{ACC} descriptors

For normalised values, contraction time had a significant effect on RMS, MNF, Mc_2, and μ_3 values of both MMG_{MIC} and MMG_{ACC} signals (respectively, $F_{17,13} = 5.27$ $P < 0.001$, $F_{17,13} = 2.84$ $P < 0.001$, $F_{17,13} = 7.99$ $P < 0.001$, and $F_{17,13} = 2.08$ $P < 0.001$; Figs. 2, 3). Normalised μ_3 values were lower for MMG_{MIC} (125.7 ± 15.4%) than for MMG_{ACC} (173.8 ± 15.4%) signals ($F_{1,13} = 4.86$, $P < 0.05$).

There was a significant positive correlation ($R^2 = 0.37$, $P < 0.001$) between RMS slopes estimated from MMG_{MIC} and MMG_{ACC} signals. However, MNF ($R^2 = 0.02$), Mc_2 ($R^2 = 0.19$), and μ_3 ($R^2 = 0.02$) slopes estimated from the two sensors were not correlated.

3.2 Variability of estimates of MMG descriptors

The coefficient of variation of RMS values was significantly higher for MMG_{MIC} than for MMG_{ACC} (0.249 ± 0.007 vs. 0.220 ± 0.007, respectively; $P < 0.05$, Fig. 4 and Table 1). The coefficient of variation of μ_3 values was significantly lower for MMG_{MIC} compared with MMG_{ACC} (0.427 ± 0.021 vs. 0.521 ± 0.021; $P < 0.05$, Table 1).

Table 1 Two-way repeated measures ANOVA: effects of time (contraction duration), MMG signal type (MMG_{MIC} /MMG_{ACC}) and interaction (time × MMG signal) on the RMS, MNF, Mc_2 and μ_3 coefficient of variation

Coefficient of variations	Time		MMG signal		Interactions	
	$F_{17,13}$	*P* value	$F_{1,13}$	*P* value	$F_{17,221}$	*P* value
RMS	2.21	0.005	9.02	0.01	0.88	0.60
MNF	1.63	0.058	1.06	0.32	1.55	0.08
Mc_2	1.48	0.10	0.49	0.49	1.17	0.29
μ_3	2.05	0.01	10.34	0.007	1.97	0.014

F variance ratio with degree of freedom; *P* level of significance

4 Discussion

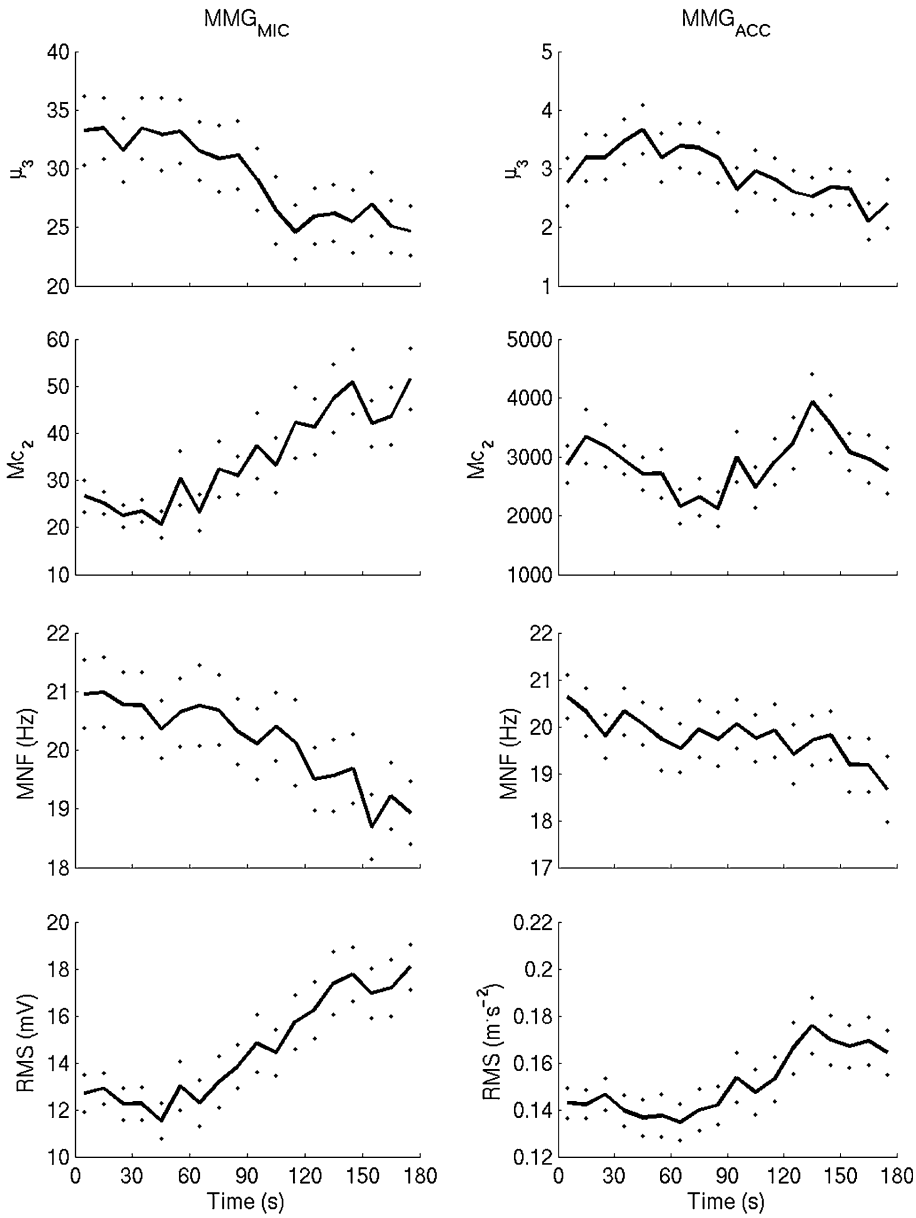
Higher order spectral moments of the MMG signal change over time, indicating a complex variation of the shape of the power spectrum with sustained contraction at 30% MVC. Moreover, despite similar trends of the time- and frequency-domain signal descriptors, the rates of change of spectral variables computed from signals of the two sensors were not correlated. There were also differences in the coefficient of variation of the estimates of RMS and third-order spectral moments obtained with the two transducers.

4.1 Changes in MMG signal properties during sustained contraction

During sustained contractions, the increase in the time-domain and the decrease in the frequency-domain descriptors of the MMG signal are usually attributed to changes in the number and discharge rate of the active motor units as well as to modifications in contractile fibre properties [15, 16]. The relative changes in time and frequency domains are function of the contraction level [6, 10, 15]. The anatomy and muscle fibre distribution also have an effect on the MMG frequency content [25]. Moreover, variations in the muscle intrinsic properties to some extent influence the MMG signal [15]. The changes in both absolute and normalised RMS and MNF values in the present study are similar to those reported in previous studies at similar contraction levels [9, 10, 15].

The second- and third-order central moments of the power spectral density provide information on the width and skewness of the MMG signal spectrum, describing more precisely slow non-stationarities [14]. The decrease in absolute and normalised MNF confirmed that the power spectral density of the MMG signal progressively compressed over time. However, the spectral bandwidth, that is, variance, increased with contraction time highlighting a variation in spectral shape during sustained contraction (Figs. 2, 3). The observed changes in spectral shape of the MMG signal are probably due to recruitment of additional motor units and changes in motor unit discharge rate with fatigue [2, 4, 11]. The effect of these phenomena on the MMG signal properties is difficult to predict due to the non-linear summation of the motor unit contributions [18]. Due to the significant changes in second- and third-order spectral moments observed in this study, it can be concluded that the first-order spectral moment is not sufficient to fully describe the changes in the MMG power spectrum.

Fig. 2 Mean (± SE) absolute root mean square (RMS), mean power frequency (MNF), second-order central moment (Mc_2) and third-order central moment (μ_3) values of MMG_{MIC} and MMG_{ACC} signals during sustained isometric contraction at 30% maximum voluntary contraction ($n = 14$)



4.2 Influence of the transducer type on MMG properties

The physical characteristics of the two transducers analysed differ largely. For condenser microphone, the frequency response declines with decreasing diameter and length of the air chamber. Therefore, it is suggested that air chamber should be at least 10 mm in diameter and 15 mm in length [21]. The microphone used in the present study might therefore not reproduce linear frequency components below 5 Hz. Microphones introduce a rigid mechanical discontinuity on the muscle surface that should be taken into consideration [16]. However, recent results indicate that the specific deformity of skin surface (microphone recordings) is less important than MMG amplitude changes [21].

The weight of the accelerometer used to record MMG signal was below the suggested limit of 5 g for accurate measurement [22]. Furthermore, contrary to other types of sensors, accelerometers record MMG signal in physical units (m s^{-2}) enabling a comparison between different studies [15]. Microphones are probably more reliable than accelerometers to record MMG signal during anisometric contractions [8] while microphones require silent environment.

Despite similar general trends with respect to the development of localised muscle fatigue (Figs. 2, 3), important differences in the MMG_{MIC} and MMG_{ACC} signals were observed (Fig. 1). The increase in bandwidth was more marked in MMG_{MIC} recordings (Figs. 2, 3) and the normalised third-order spectral moments were significantly smaller for the microphone

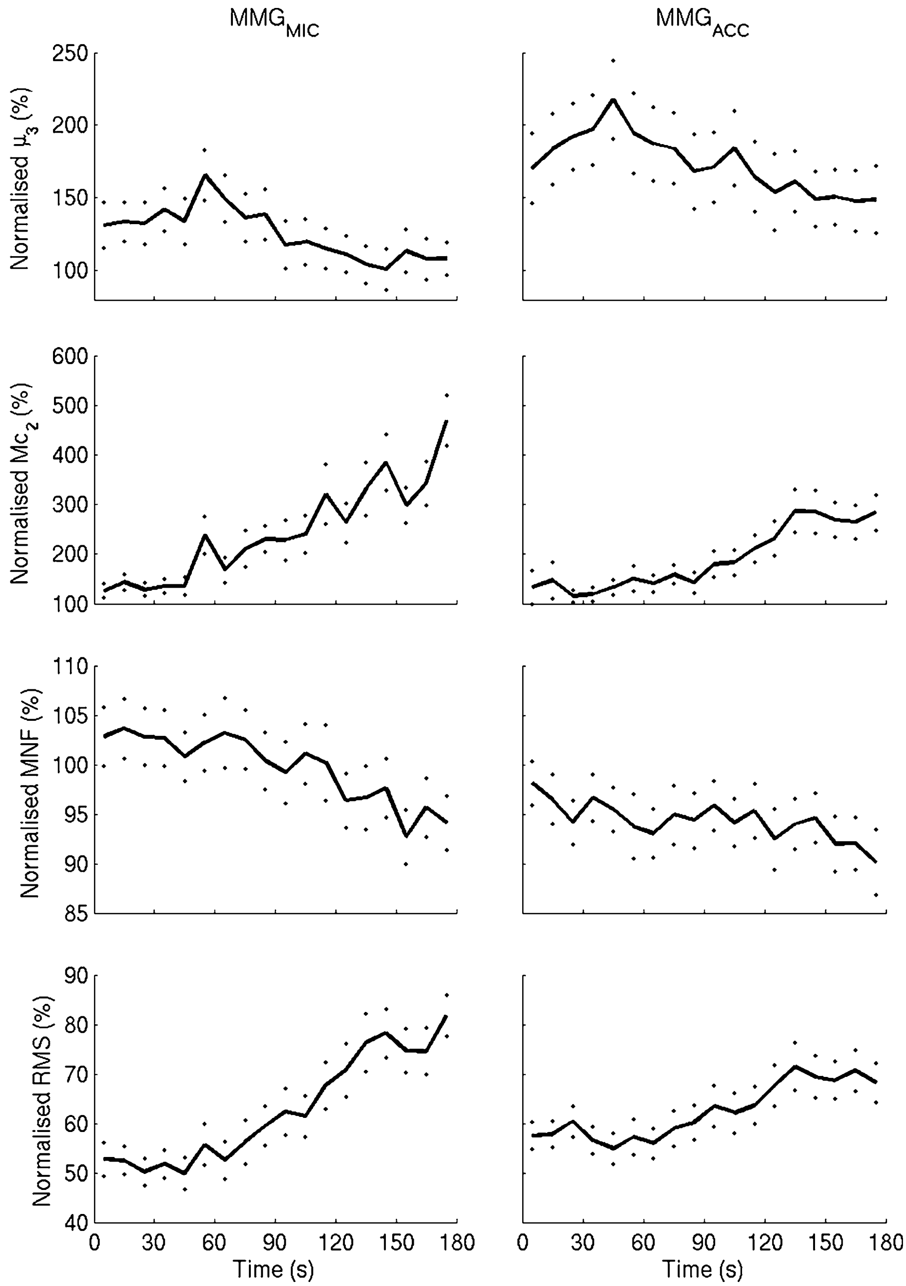


Fig. 3 Mean (±SE) normalised root mean square (RMS), mean power frequency (MNF), second-order central moment (Mc_2) and third-order central moment (μ_3) values of MMG$_{MIC}$ and MMG$_{ACC}$ signals during sustained isometric contraction at 30% maximum voluntary contraction ($n = 14$)

compared with accelerometer. Moreover, a lack of correlation was found between the rates of change of all spectral moments for MMG$_{MIC}$ and MMG$_{ACC}$ recordings. This most likely cannot be explained by the different location of the two transducers since it has been previously observed that for distances up to 44 mm the location of the transducer does not significantly affect amplitude and spectral MMG features in the biceps brachii muscle [3]. Thus, the observed differences are attributed to different characteristics between the two transducers. During voluntary contractions, the frequency response of the MMG$_{MIC}$ might be affected by skin deformation due to the fact that the microphone is attached to the skin and by skin folds thickness [7].

Accelerometers have been indicated as the most reliable tool for MMG recordings during isometric contractions together with laser distance sensor [16]. Accordingly, in the present study we observed a lower coefficient of variation of RMS when measured from MMG$_{ACC}$ than from MMG$_{MIC}$. On the other hand, the coefficient of variation of normalised third-order spectral moments, not investigated in previous studies, was larger for MMG$_{ACC}$ than for MMG$_{MIC}$ signals even though this can partly be explained by the relative low repeatability of skewness [12]. The present results obtained during isometric sustained contraction, confirm that the information contained in microphone- and accelerometer-based MMG signal is different [21], making comparison between studies difficult.

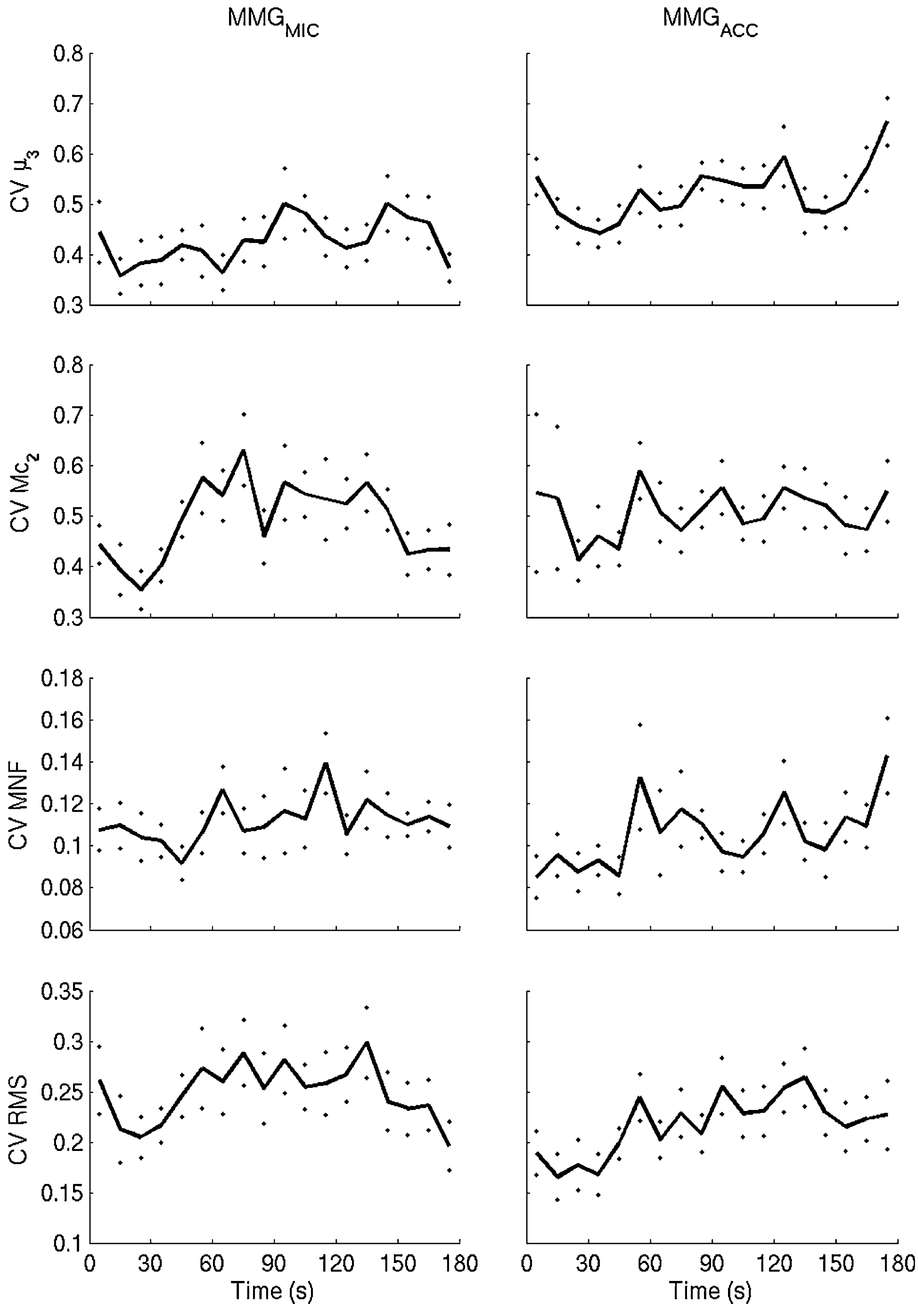


Fig. 4 Mean (± SE) coefficient of variation of root mean square (RMS), mean power frequency (MNF), second-order central moment (Mc_2) and third-order central moment (μ_3) of MMG_{MIC} and MMG_{ACC} signals during sustained isometric contraction at 30% maximum voluntary contraction ($n = 14$)

5 Conclusions

Changes in the power spectrum of MMG signals cannot be described exclusively with the first-order spectral moments. Moreover, the temporal and spectral descriptors of MMG signals and their changes over time due to sustained contraction are different when using a microphone or an accelerometer. Thus, comparison of studies that apply the two transducers may be critical.

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