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Electromechanical delay of abdominal muscles is modified by low back pain prevention exercise

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The objective of the research was to assess the effect of a 4-week-long training program on selected parameters: electromechanical delay (EMD) and amplitude of electromyographic signal (EMG). Fourteen female students of the University School of Physical Education participated in the study. Torques and surface electromyography were evaluated under static conditions. Surface electrodes were glued to both sides of the rectus abdominis (RA), external oblique (EO), and erector spinae (ES) muscles.

The 4-week-long program was aimed at strengthening the abdominal muscles and resulted in increased EMD during maximum torque production by flexors of the trunk, increased amplitudes of the signals of the erector spinae ($p = 0.005$), and increased EMG amplitude asymmetry of the lower ($p = 0.013$) and upper part ($p = 0.006$) of the rectus abdominis muscle. In a training program composed of a large number of repetitions of strength exercises, in which the training person uses their own weight as the load (like in exercises such as curl-ups), the process of recruitment of motor units is similar to that found during fatiguing exercises and plyometric training.

Key words: *electromyography, symmetry, female*

1. Introduction

Electromechanical delay (EMD) is defined as the time shift between the onset of electromyographic signal (EMG) in a muscle and the first occurrence of force produced by this muscle. EMD values range from several milliseconds to approximately 200 ms [11]. It is believed that EMD is influenced by factors such as propagation dynamics of the action potential, excitation-contraction coupling, and stretching of the series elastic component of a muscle (SEC) by its contractile component [3]. Differences in EMD have been reported with respect to gender [6], age [24], type of muscle activity [3] and muscle fatigue [25]. EMD has also been found to correlate with the force produced during maximum voluntary contraction (MVC), rate of force development, muscle fibre composition and peak torque [23]. Other authors, such as Kubo et al. [14] and Zhou et al. [25], have reported changes in EMD after intensive training, reflecting structural and functional properties of muscles.

The estimation of EMD is difficult, especially when one wants to establish precise relations between the EMG signal, the forces and moments of forces produced, and the resulting movement pattern. Thus, some investigators assume constant values of EMD to obtain time profiles of EMG, force, and moment of force [3] neglecting the fact that EMD may depend on external loads.

The influence of various forms of training on EMG signal properties is an important consideration in competitive sports, and accordingly, the literature is large [19]. EMD is acknowledged to represent a correlation between EMG onset and force time course, and there is no general agreement on whether its influence is favourable. Usually authors avoid such interpretations and restrict themselves to merely describing their results, as in Grosset et al. [10], in which a decrease in EMD after endurance training and

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increase in EMD after plyometric training were found. The influence of various types of exercise on the EMD phenomenon has been primarily investigated for the upper [3] and/or lower limbs [25] and there are no reports on the EMD phenomenon for flexors and extensors of the trunk. This lack is likely a consequence of methodological difficulties.

Our interest in the effect of training on neuromuscular coordination assessment based on selected parameters (the amplitude of the EMG signal and EMD) of flexors and extensors of the trunk is dictated by their important function in spine stabilisation. The constantly increasing popularity of training programs under the banner of a "healthy spine" requires an objective assessment of how this specific type of training affects the EMG activity patterns of the muscles being trained. Contrary to competitive sports, this type of training does not employ maximum training loads. For example, muscles that stabilise the spine do not need to be trained at maximum loads as in competitive sports. Therefore, the influence of this type of training on EMG activity of muscles may be different.

The aim of our research was to assess the effect of a training program based on spine-safe strengthening exercises for abdominal muscles that are routinely used in spine pain prevention on EMG. We propose the hypothesis that the changes in control of excitation of the muscles that stabilize the spinal column (evaluated by EMD) will occur after a 4-week training program used in spine pain prevention.

Abdominal muscles are part of the muscle groups defined in the literature as the "muscle corset", whose role is primarily to stabilize the spine and prevent overloading. The research shows that 50% of the working population of adults suffers from the "low back pain" syndrome (LBP) [22]. One of the reasons is that the ligaments of the spine muscles are not able to support loads even much smaller than the weight of the body. This causes asymmetric pressure on intervertebral discs resulting in pain. As the external loads in the human muscular system are transmitted in sequence by muscles, ligaments, joints and bones, weakening the muscles can cause problems even with relatively small loads experienced in everyday life. Therefore, many studies emphasize the need for strengthening the abdominal muscles, as well as searching for exercises aimed at strengthening them [1]. Scientific studies emphasize the importance of quantitative identification of abdominal exercises and one of the problems to be solved deals with symmetry of muscle activity in the exercises, intended to stabilize the spine. An additional objective of the experiment was therefore to answer the question of whether symmetrical exercises (such as curl-ups) actually produce symmetrical muscle activity.

2. Materials and methods

2.1. Subjects

The study included 14 volunteer right-handed female students from the Faculty of Physical Education (mean ± SD: age = 21.57 ± 1.9 years; height = 168 ± 5 cm; body weight = 60.06 ± 7.9 kg). Persons of one sex (women), similar age (20–26 years), similar level of motor activity, and similar build were selected to enhance the representativeness of the results. All of the subjects were informed of the objectives and procedures of the experiment and signed an informed consent statement. The participants of the experiment were healthy and did not suffer from low back pain. The experiment was approved by the local ethics committee.

2.2. Program of strengthening exercises

The training program lasted 4 weeks. Participants exercised 3 times a week (Monday, Wednesday, and Friday), and were supervised by an instructor. The exercises consisted of flexing the trunk while laying on the back to such a position that the lumbar section of the spine still remained in contact with the floor (curl-up exercise). Attention was paid to ensure that angles in the hip and knee joints equalled 90°, upper limbs were flexed at the elbows, and hands (placed at the back of the head) applied no force on the head towards the chest.

The training sessions were individualized. A participant was asked to perform as many sets of a particular exercise as possible within one training session. The number of repetitions within a set increased by 10 each week, that is, the participant performed 10 the first week and 40 by the end of the training period.

Each training program was ended when abdominal muscle fatigue appeared (pain in abdominal muscles). During the 4 weeks of training, each person performed an average of 3,000 (±SD = 56) curl-up exercises. Stretching exercises of abdominal muscles were performed at the end of each training session.

2.3. Experimental procedure

The subjects were asked to respond to a cue by producing a maximum voluntary torque of flexors and extensors of the trunk in the sagittal plane. Measurements of the torque and EMG signal were performed twice: before and after 4-week-long strength training of abdominal muscles.

To record and analyse the EMD data, it was necessary to simultaneously use surface electromyography and torque measurement under static conditions – during maximum voluntary isometric contraction (MVIC). The EMD was defined as the time interval from the onset of EMG in the respective muscle to the onset of torque development. Torque measurement was carried out on a multifunctional chair (SUMER, Opole, Poland, UPR-01 A/S). The technical characteristics of the measuring device were as follows: the measuring range of the tensometric head was 0–500 N m, the relative error of the tensometric bridge was equal to 0.5%, direct current amplifier with calibrated amplification $k = 470$, bandwidth 0–1 kHz, and temperature drift of zero 0.6 $\mu V \cdot {}^{\circ}C^{-1}$.

The torque measurements were performed on the multifunctional chair according to the previously described method [21]. The subject assumed a sitting position on the measuring stand. Hip joint and knee joint angles were equal to 90°, and the hip joint axis was aligned with the axis of the dynamometer. To minimise the influence of the other muscle groups through so-called muscle torque transfer, the upper extremities were crossed on the chest, and the pelvis, thighs, and shanks near the ankle joints were fastened with stabilising belts. To measure EMG and the torque of abdominal muscles, the band resistance of the measuring device was applied to the front of the trunk at the chest (Fig. 1). To measure EMG and the torque of the erector spinae muscles (ES), the resistance of the measuring device was applied to the back of the trunk at the scapulae (Fig. 2). The length of the lever arm of the external force was adjusted individually before each measurement, accounting for the anatomical build of the subjects.

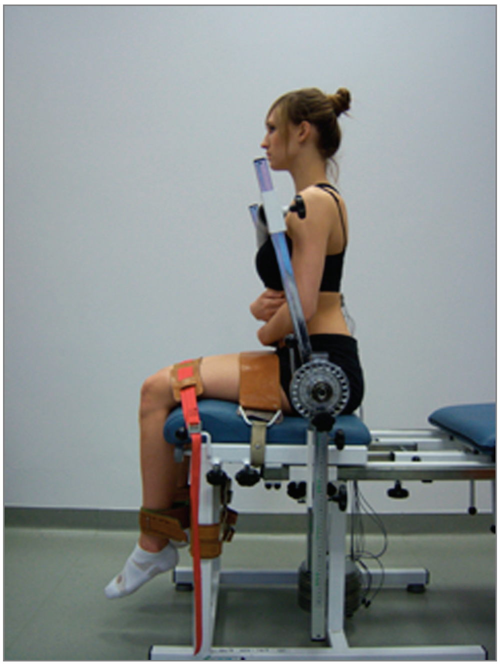

Fig. 1. Measurement of the maximum torque and EMG activity of abdominal muscles

Fig. 2. Measurement of the maximum torque and EMG activity of back muscles

During the measurements, the subjects were encouraged by the investigators to produce the maximum torque as fast as possible. The subjects were instructed to keep their head and neck in one line to minimise the effect of deepened lordosis.

2.4. EMG data processing

The measurement of the muscular torques under static conditions and a simultaneous recording of the EMG signal were performed for muscles representing the groups of flexors and extensors of the trunk. Surface electrodes were placed on the right and left side of the ES, external oblique (EO), and rectus abdominis (RA), and additional electrodes were placed on both the upper and lower parts of the RA (Fig. 3).

This special placement of electrodes on the RA muscle (i.e., at both its right and left side and at both its upper and lower part) was dictated by its specific structure. A similar approach was adopted by other authors [4]. The electrodes on the right and left side of the ES were placed laterally at 3.5 cm from the processus spinosus of the first lumbar vertebra in a vertical orientation (Fig. 4).

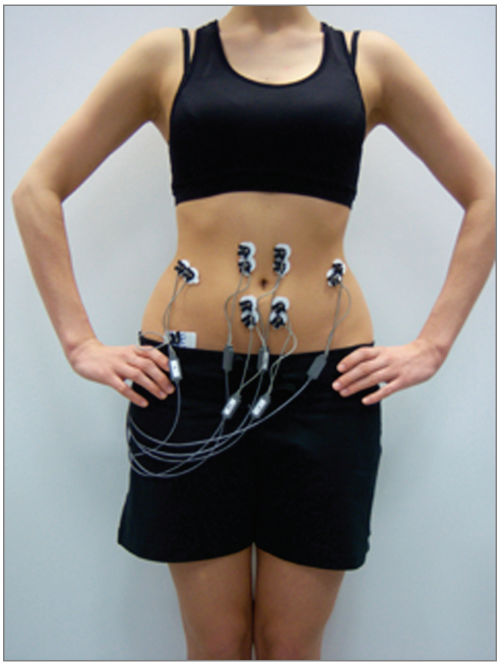

Fig. 3. Electrode placement on the right and left side of the RA (upper and lower part) and EO muscles (as in Ng et al. [16])

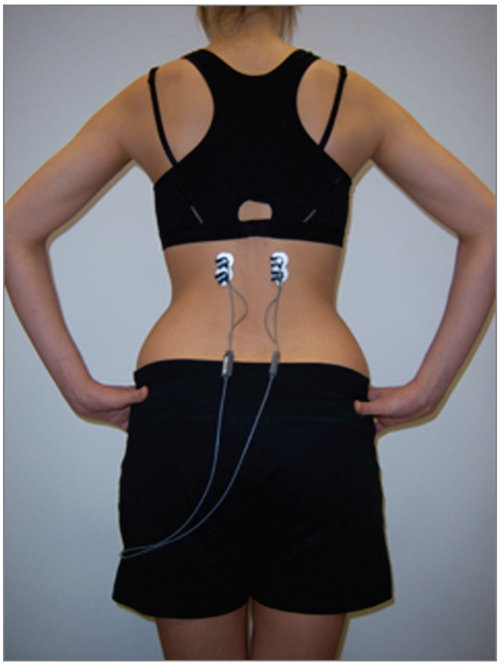

Fig. 4. Electrode placement on ES muscle (as in Freriks et al. [8])

The surface electrodes were placed according to the rules for the best EMG signal reception available in the literature [16] and according to the lines of action of the muscles, accounting for individual differences in the anatomical build of the subjects. Surface Ag/AgCl electrodes with solid gel (Noraxon USA, Inc.; Nr 272) were placed in a bipolar configuration on the bellies of the muscles parallel to muscle fibres; the distance between electrode centres was = 20 mm. The complete set comprised 8 pairs of active electrodes and one reference electrode, the latter being placed on the skin at an electrically passive location (anterior superior iliac spine). The skin was prepared according to the guidelines of the SENIAM project [8]. The 8-channel electromyographic device Octopus AMT-8 (Bortec Electronics Inc., Calgary, Alberta; CA) was used to acquire EMG signals. The amplifier bandwidth from 10 to 1,000 Hz and the common-mode rejection ratio was 115 dB. The EMG signals were sampled at 1,000 Hz by using an analog-to-digital converter based on a 16-bit analog-to-digital board.

2.5. EMG signal processing

The raw EMG signal and torque were both recorded on a PC computer with BioWare® (V.3.2.6) software. The obtained files were then exported to the Matlab environment, in which the onset of muscle activity and torque production was determined with the two-stage EMG onset detection method [7], [20]. This method is based on the analysis of differences in signal strength between the part of the signal that precedes the activity and the part in which the activity occurs. During the first stage, each measuring point was assigned a probability of being the initial moment of activity, whereas during the second stage, the initial point of activity was chosen from the area for which the estimated probability was the highest. This method allowed for avoiding phase lags, which are typical of one-way filtering.

2.6. Statistical analysis

The Wilcoxon signed-rank test was used to assess the effect of strength training on EMD. The results of the statistical analysis include: N (the number of subjects), and p (the probability level for the Wilcoxon test). Table and graph contain the median (Me – middle value) and quartile deviation (Qc). The level of significance (α) was set at 0.05.

3. Results

We found an increase in EMD after strength training of abdominal muscles by 31.1% to 57.8%, and these differences were statistically significant for the RA muscle in its upper part on the right side ($p = 0.04$) and in its lower part on the left side ($p = 0.03$). The increase in EMD was also statistically significant for the EO muscle on its left side ($p = 0.01$). EMD values did not change after strength training for the ES muscle (Fig. 5).

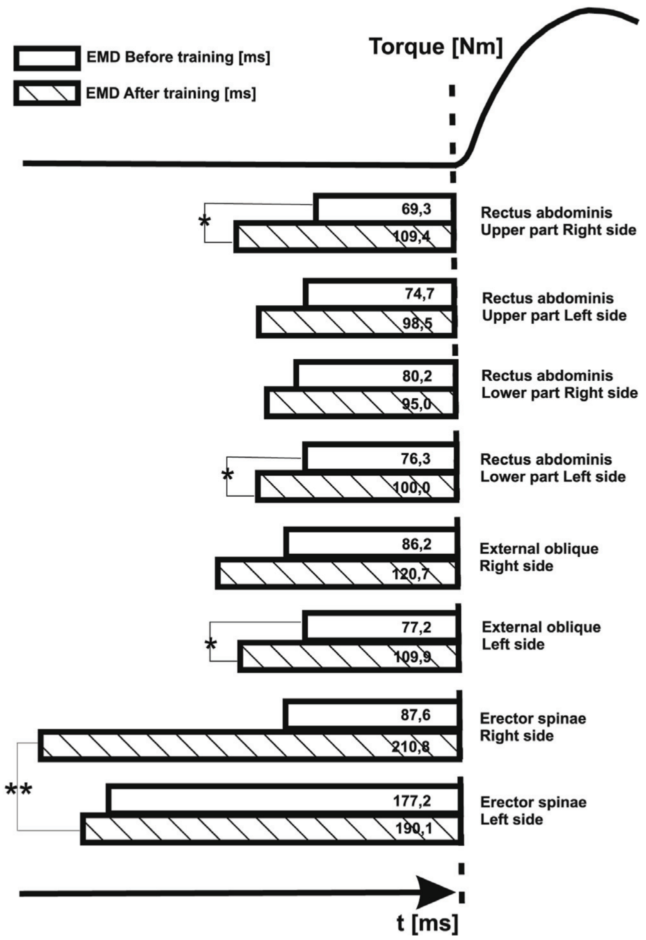

Fig. 5. EMD (ms) of examined muscles before and after training
Note. * Indicates significant increase from before to after training.
** Indicates significant differences between right and left side of the muscles

The amplitude of the EMG signal recorded from the muscles investigated before and after training was assessed in the next step of analysis. No changes were observed in EMG signal amplitude for the abdominal muscles (RA and EO). In contrast, the Wilcoxon signed-rank test showed significant differences in EMG signal amplitude for the back muscles on the right side (53.11 vs. 55.54 μV, $p = 0.005$) (Table 1).

Table 1. EMG signal amplitude [μV] of the right and left side of the investigated muscles before and after the strength-training program. Data are Me (±Qc) ($n = 14$)

Training	Muscles	Right side (Me (±Qc))	Left side (Me (±Qc))
Before	Rectus abdominis *Upper part*	46.17 (47.62)	55.85 (36.78)
	Rectus abdominis *Lower part*	74.42 (42.14)	64.62 (40.34)
	External oblique	108.01 (45.28)	128.28 (30.88)
	Erector spinae	53.11 (21.37)	62.14 (27.52)
After	Rectus abdominis *Upper part*	51.28 (28.94)	58.19 (42.27)*
	Rectus abdominis *Lower part*	89.93 (45.34)	61.97 (34.26)*
	External oblique	124.43 (52.95)	115.80 (61.03)
	Erector spinae	55.54 (29.21)	63.96 (33.25)

Note. * Indicates significant differences between right and left side of the RA muscles.

The next stage of analysis was to assess the strength of correlation between the amplitude of the EMG signal and the values of EMD both before and after training. Following the selection of non-parametric statistical methods, Spearman's rank correlation coefficients were used. The EMG signal amplitude displayed a strong correlation with EMD only after the training program. Moreover, this correlation was found only for the RA muscle on the right side of its lower part ($r = 0.656$), and for the left EO muscle ($r = 0.538$).

The symmetry of EMD values and EMG signal amplitude was assessed for the right and left side of the investigated muscles before and after strength training. Statistical analysis showed symmetric EMD patterns for abdominal muscles (RA and EO) both before and after the training program. Asymmetric EMD patterns were observed in only one case: for the ES muscle after completion of the strength training program ($p = 0.013$) (Fig. 5).

Similar analysis of the EMG signal amplitude showed the prevailing symmetric patterns of this quantity. The differences were significant in two cases (also after training): for the RA muscle in its upper part ($p = 0.006$) and in its lower part ($p = 0.013$) (Table 1).

4. Discussion

The training program applied in this study comprised strength and endurance exercises aimed at strengthening the muscles that stabilise the spine. Regarding the duration of the training program, it was assumed that the organisation of muscle recruitment would change after the four weeks of training, which would manifest itself through appropriate changes in selected features of the EMG signal.

This study describes a detailed analysis of the influence of strength training on the phenomenon of EMD in selected abdominal and back muscles. The results suggest an increase in EMD after completion of the training program. In our opinion, an increase in EMD occurred because a change in organization of muscle excitation may have taken place as a result of performing the exercises slowly. A significant increase in EMD after strength training was observed for the RA muscle in its upper part on the right side and its lower part on the left side. A significant increase in EMD was also observed for the EO muscle but only on the left side. No significant changes in EMD values were found for the ES muscle. Based on an analysis of the literature, EMD is a sensitive feature to the conditions of measurement. It may change under the influence of fatigue and the type of physical exercise. Zhou et al. [25] reported a significant increase in EMD for the rectus femoris muscle (from 40.4 to 63.4 ms) as a result of fatigue. They noted no significant changes in EMD after a 7-week-long sprinting bicycle training program. In a study aimed at assessing the elastic properties of the quadriceps femoris tendons under fatigue, Kubo et al. [15] also observed an increase (from 60.6 to 70 ms) in EMD after a muscle fatigue test (MFT). In another study [14] a decrease in EMD for the vastus lateralis muscle (from 52.6 to 37.3 ms) was found after isometric strength training. Grosset et al. [10] compared the effect on the EMD of two 10-week-long training programs, endurance focused and plyometric, and found inverse proportionality between EMD and musculotendinous stiffness. According to these authors, endurance training caused a decrease in EMD and an increase in musculotendinous stiffness, whereas plyometric training resulted in increased EMD and decreased musculotendinous stiffness. According to their interpretation, endurance training, which is known for preferential activation of slow-twitch, stiffer muscle fibres, leads to decreased EMD and increased stiffness. In plyometric training, which requires the recruitment of fast-twitch, more compliant fibres, the opposite behaviour takes place. Häkkinen and Komi [12] did not notice any significant changes in EMD measured under conditions of reflex contraction before and after a 16-week-long strength-training program applied to the quadriceps femoris muscle. In a subsequent study [13], the same authors did not notice any significant changes in EMD following 24-week-long strength training of the quadriceps femoris muscle. Other studies have also investigated the effect of passive stretching on EMD [6]. This relationship has special importance in competitive sports, in which stretching exercises are used prior to training or competitions to increase the range of motion, enhance muscle elasticity, and improve their maximum efficiency. Costa et al. [5] focused their research on EMD changes resulting from passive stretching of plantar flexors. Their research showed that 20 minutes of passive stretching increases EMD, which suggests that stretching, may have lengthened the muscle's elastic component, thus contributing to a "less stiff" force transfer from the contractile component to the bone. These authors suggest that stretching may have caused more slack in the musculotendinous system, which may have weakened the contractile component by requiring more time (increased EMD) to produce external force. In our study, in addition to EMD, the EMG signal amplitude was examined before and after strength training of abdominal muscles. Increases in the abdominal muscles EMG amplitude were found as a result of training, except for the left rectus abdominis muscle in its lower part and the left external oblique muscle. These changes were not statistically significant. Our results also showed an increase in the EMG signal amplitude for the ES muscle, with the left side prevailing. However, a statistically significant change was found for the right side only.

One of the causes of low back pain (LBP) is asymmetric pressure of vertebrae on intervertebral discs caused by asymmetry of muscle forces stabilising the vertebral column. That is why "healthy spine" directed training programs focus on symmetric exercises increasing the strength of flexors and extensors of the trunk. The curl-up exercise on which our training program was based is a symmetric exercise. Symmetry was further enhanced by following the guidelines for upper limb position. It could therefore be expected that symmetric exercises would result in symmetric electric activity patterns of muscles. Our results confirmed this hypothesis by showing symmetric EMD patterns for the right and left side of the RA and EO muscles both before and after the strength-training program. A statistically significant asymmetry of EMD was observed for the ES muscle after the 4-week-long training program. The present results agree well with the conclusions of our previous studies in which the EMD for flexors and extensors of the trunk was examined in physical education female students, a more diverse group compared with this study because it included competitors in various sport disciplines [20].

The next feature of the EMG signal analysed in terms of symmetry was its amplitude. We anticipated that symmetric exercises of abdominal muscles would improve symmetry of the functional potential of the RA and ES muscles. However, contrary to our expectations, although the EMG amplitude was symmetric before training, asymmetry appeared after training for the RA muscle in its upper and lower part (Table 1). The observed asymmetry may be a result of the phenomenon of compensation of electric activity. The present results differ from those obtained in our previous experiments, in which symmetry of the EMG amplitude was examined during isometric exercises, and subjects did not produce maximum values of the moment of force of trunk flexors [17]–[18]. In those studies, there was no difference between the right and left side of the RA. Moreover, an asymmetry of activity of the ES muscle was found in those experiments. This is in contrast to the findings of the present experiment, in which symmetry of the EMG signal amplitude between the right and left side was confirmed for the extensor spinae muscle.

The fact that symmetry of the EMG signal amplitude may depend on experimental conditions is cited in studies by other authors. Asymmetry of the EMG signal of back muscles, ES and trapezius was found by Furjan-Mandić et al. [9]. In that study, higher electric activity was observed during all of the exercises on the right side of the examined muscles. In contrast, however, Axler and McGill [2] described a different asymmetrical pattern: higher activity on the left side than the right side for the RA and the opposite for the EO and internal oblique muscles. The symmetry of EMG activity during dynamic sit-up exercises of abdominal muscles was analysed in that study.

5. Conclusions

Four-week-long program of strengthening exercises of abdominal muscles: 1. lengthened the EMD during production of maximum torque of flexors of the trunk (RA: upper part left side, RA: lower part left side and EO: left side); 2. did not increase the EMG signal amplitude of the examined muscles, except for the ES muscle; and 3. increased asymmetry of the EMG signal amplitude in the lower and upper part of the RA muscle. A correlation was found after completion of the training program between the EMD and the EMG signal amplitude.

Acknowledgments

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