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Electromyographic activities of muscles in the shoulder and elbow joints during elbow flexion-extensions with different velocities in the sagittal and horizontal planes

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Abstract

Study aim: Properly processed surface electromyographic signals (EMGs) provide a suitable means for the estimation of muscle activity, including their synergistic and antagonistic action. This study aimed to investigate changes in the activity of elbow and shoulder muscles due to changes in the velocities of elbow flexion/extension motions in the sagittal and horizontal plane without and with an additional load of 0.5 kg on the wrist using processed EMGs of six muscles and the angle of the elbow joint.

Material and methods: Experimental data from ten healthy volunteers were processed. The EMGs from each part of a motor task – maximal elbow flexion from an initial downwards arm position, rest in the maximally flexed position and maximal extension – were filtered, rectified, and normalized according to suitable maximal isometric tasks. The areas under the obtained curves for each part, called activities, were subjected to statistical analysis including calculations of correlation coefficients between the activities of different muscles.

Results: In general, muscle activities were heterogeneous and strongly individual. The angular velocity was higher for movements without additional weight. Sagittal flexion velocity was higher than the horizontal one. The muscle activities for all subjects for all muscles are presented and discussed.

Conclusions: The main conclusions were as follows: m. biceps brachii, m. brachialis and m. deltoideus pars clavicularis showed the main activity, and their activity increased with increasing velocity but not with increasing load; m. deltoideus pars spinata and m. triceps brachii had slow activity. Surprisingly, the small m. anconeus was much more active than the m. triceps, especially during extension.

Keywords: Elbow – Shoulder – EMG – Movement – Different velocities

Introduction

Investigation of the activity of the human upper limb muscles is motivated by several factors. First, the following questions are interesting from a scientific perspective: How does the human nervous system controls muscles (muscle motor units) during different motor tasks? [25, 27, 32] What is the dependence between muscle forces and their electromyographic signals (EMGs)? [12, 17, 30] Why is antagonistic muscle activity necessary? [18] Why are muscle synergies important? [9, 15] Can EMG signals be used to verify the muscle forces calculated using different mathematical models? [16, 20, 35]. Second, muscle activities (respectively, muscle EMGs) and their changes are important to estimate different neuromuscular diseases and their medical treatment [1, 4, 22]. Third, this issue is important to develop control of different technical devices (orthesis, exoskeletons) where EMG signals are used as control signals [7, 14, 31, 33]. Even in a simple movement in one plane and one degree of freedom (DoF), many muscles show EMG activity [6, 29]. Some of them perform motion (synergistic activity [9, 19]), and some ensure stability in joints; antagonistic activity is also observed for fast motions [15]. Therefore, the activity of muscles of the upper limb during different motor tasks is very complex and very important. Moreover, finding quantities to estimate muscle activity and comparing them with some kinematic parameters of motion is very difficult. Therefore, many EMG investigations consider only one simple motion and a small number of muscles. Often, elbow flexion/extension in combination with pronation/supination

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[32] or horizontal point-to-point movement involving the shoulder and elbow muscles [13, 15] is experimentally investigated.

Systematic investigations of the changes in muscle activities due to increasing movement velocity are lacking. This issue is important since increases in movement velocity can increase the inertial forces, which can change the external joint moment. Consequently, this change can affect muscle activity – for example, from flexors towards extensors [28]. As a result, the load in the subsequent joints (for example, shoulder versus elbow) will be changed due to changes in the joint reactions.

The current study aimed to investigate changes in the activities of muscles that drive elbow and shoulder joints due to changes in the velocities (from very slow to the fastest) of the flexion/extension motions in the elbow joint and due to adding an additional load of 0.5 kg to the wrist in the sagittal and horizontal plane by measuring EMG signals of six muscles and the angle of the elbow joint.

Materials and methods

Participants

The experiments were performed on 15 healthy volunteers. After an in-depth review of the video files from a NORAXON system with motor task performance and initial data processing, only 10 participants whose EMGs were free of abnormal spikes and artefacts were selected, 4 of whom were men and 6 of whom were women. All 10 volunteers (age 26–64 years, mean 44 years, mean height – 1.69 m, mean body mass – 68 kg) were right-handed. The experiments comply with the Declaration of Helsinki (ethical principles for medical research involving human subjects). The volunteers had no neurological or musculoskeletal disorders. They were informed in detail about the experimental procedure, filled in injury cards and gave informed consent. During all tasks, the person was seated in a chair without an elbow rest. Participants were given verbal instructions and were allowed to perform several trial attempts before the data were recorded. The 8-channel telemetric system Telemyo 2400G2 of Noraxon Inc. was used for on-line monitoring and saving the experimental data for further off-line processing. The surface EMG signals were taken by “Skintact-premier” F-301 Ag/AgCl circle electrodes (30 mm diameter). Before placing the electrode, the skin was shaved and cleaned with alcohol and contact gel was placed on the electrodes. The angle of elbow flexion/extension was measured using a 2D flexible electrical Noraxon goniometer connected to the system. All motor tasks were performed by the right hand of the subject (Fig. 1). The sampling frequency was 1500 Hz, and the duration of each motor task was one minute. The investigated muscles were the pars clavicularis and pars spinata of m. deltoideus (DELcla, DELspi); the common body of the biceps brachii muscle (BIC); the caput longum of the triceps brachii muscle (TRI), the brachialis muscle (BRA) and the anconeus muscle (ANC). The locations of the sensors were chosen according to the recommendations on the web page http://seniam.org (Fig.1). A PC camera monitored and stored the behaviour of the subject during the experiments. The goniometer was calibrated for each person before the start of the experiments.

Experimental protocol

The following motor tasks were performed consecutively:

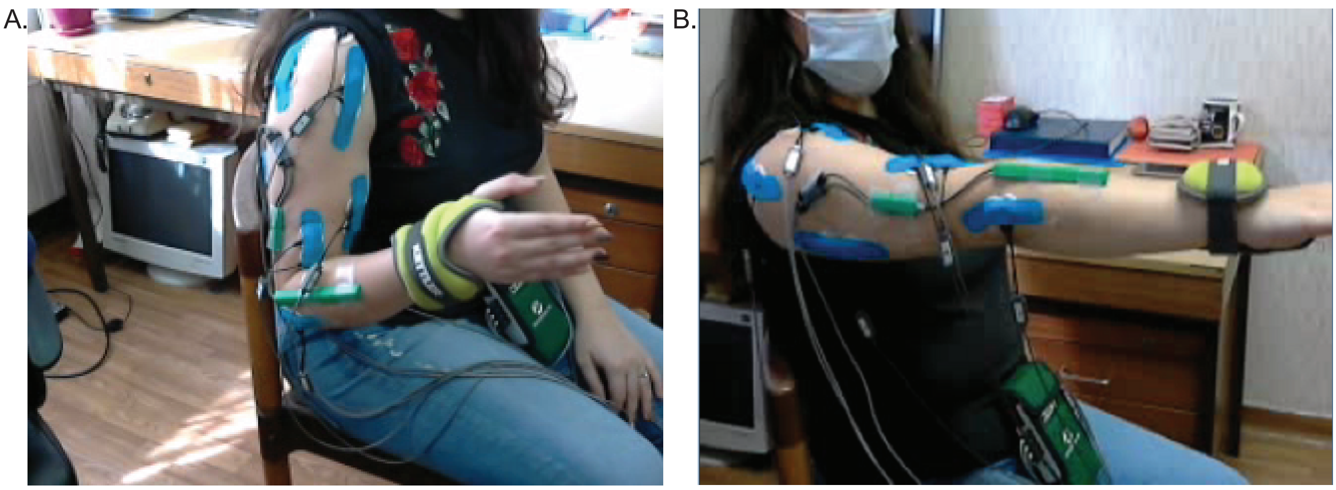

Figure 1. Experimental setup. The placement of the electrodes and flexible goniometer are shown; a wristband with a weight of 0.5 kg was placed on the wrist. A. Movement in the sagittal plane. B. Movement in the horizontal plane

- 1. Rest position – The right hand and arm were in a relaxed position, downwards, beside the body, and the thumb pointed forward; the participant held the upper arm in this position for one minute to inspect the signals for abnormal noise.
- 2. Maximal isometric exercise contractions – The subject was asked to take several positions of the arm concerning the elbow and shoulder joints. The examiner applied force distally to the bone lever to provoke a maximum effort of the investigated muscles subsequently in a static position.
- 3. From the rest position, maximal flexion in the elbow in the sagittal plane was performed, after which a 5-second rest in the maximal flexion position was held. Subsequently, maximal extension to the rest position was performed; these series (parts) of motor tasks were performed four times with different velocities, from very slow to fastest, and these velocities were controlled by a computer program. A special program designed for the Tabata workout was used to regulate the movement and rest cycles. The subject watched on the screen, on which colours and numbers were visualized. A green colour indicated movement, and a red colour indicated a static position. A simultaneous screen timer was shown on the screen counting the seconds at each interval. In addition, a special sound signal marked the beginning and ending of the flexion/extension. The times for flexion and extension were 10, 6, 2 and 1 seconds consecutively, from very slow to very fast (hence four velocities, from V_1 to V_4). The rest at the end positions (maximal flexion and maximal extension) was 5 seconds.
- 4. A wristband with a weight of 0.5 kg was placed on the wrist (Fig. 1), and the same flexion-rest-extension motor tasks with different velocities from the previous points in the sagittal plane were performed.
- 5. The upper arm was stretched forward in the horizontal plane, and the palm was pointed down; from this initial position, four flexion/extension motions in the elbow with four different speeds were performed with a rest of 5 seconds during maximal flexion and maximal extension.
- 6. The movement task was the same as above: controlled flexion and extension motions with a rest between them in the horizontal plane but with a wristband with a weight of 0.5 kg placed on the wrist.

Between different exercises, the participant rested for several minutes to avoid muscle fatigue.

Experimental data processing

The experimental data files were stored on a computer disk as text files for further off-line processing. They contained 8 columns: time, EMGs of the 6 muscles and elbow flexion/extension angle in degrees. The EMG data are in microvolts, and the angle unit is degrees.

First, the experimental data for EMGs during the rest experiments were processed. They were filtered (Butterworth high-pass filter, 4^{th} order, cut-off frequency 20 Hz; Butterworth low-pass filter, 4^{th} order, cut-off frequency 250 Hz [29]). The filtered data were visually examined for artefacts (from inappropriate placement of the electrodes, currency influence, and internet influence). Subsequently, for a chosen interval of 5 seconds, Fourier analysis was performed, and frequency-power graphics were visually inspected (the number of samples was 2048) [29].

Second, the data from the maximal isometric tasks were processed. The EMGs were filtered with the same filters, and rectified, a time interval without artefacts was chosen (because the instructor manipulation can significantly influence the signal during these tasks by touching the electrodes, moving the cables, etc.) and maximal values of the amplitude of the signal within this time interval were calculated. The maximal values of the amplitudes for all maximal isometric tasks for all 6 muscles were calculated and they were the coefficients for the normalization of the EMGs of the respective muscle EMGs during other movement tasks.

Third, for all EMGs during flexion-rest-extension motor tasks with the four velocities without and with load in the wrist, the following calculations were performed: filtration using the two mentioned filters and normalization to the calculated coefficients. The normalization was conducted according to the calculated coefficients for the respective muscle and respective subject measured during maximal isometric tasks. Since each motor task lasted one minute, different numbers of movement cycles (parts) were performed. Using visual examination, only one cycle was chosen. The start and end of flexion and extension motions were determined visually based on program and video information, and the time period during rest in the flexed position was also determined (see Figs. 2 and 3). In these three time intervals (duration of flexion and extension and the time interval for rest), the EMG data were rectified and smoothed (20 samples). The area under the obtained curves was calculated and divided into the respective time intervals. This parameter was called "activity". Before conducting statistical analysis, outliers were removed using mean and range calculations. Any values that were outside the range of mean ± 3 times the standard deviation of the variable were identified and removed from the dataset. The obtained values were statistically analysed using standard functions in Excel. Correlation coefficients between muscle activities were also calculated.

The measured angle was sufficiently smooth and did not need more processing.

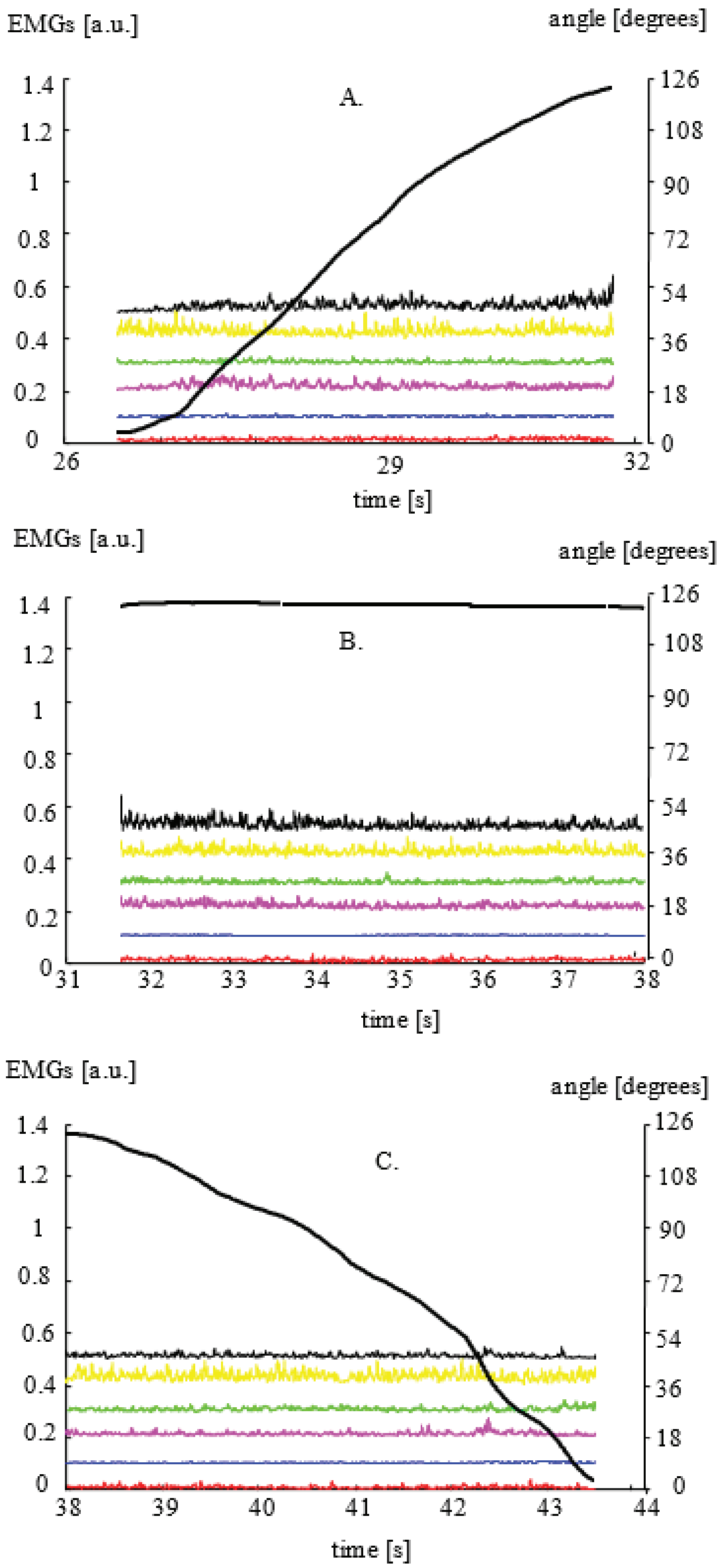

Figure 2. The chosen movement in the sagittal plane with 2nd velocity, subject №8. A. The chosen flexion. B. Rest. C. Extension. The black bold line is the measured angle. The processed EMGs are coloured as follows: DELcla – red; DELspi – blue; BIC – magenta; TRI – green; ANC – yellow; BRA – black. The EMGs are filtered, normalized, rectified, and smoothed. For better visualization, each successive EMG of the muscle is shifted up by 0.1. a.u. (arbitrary unit)

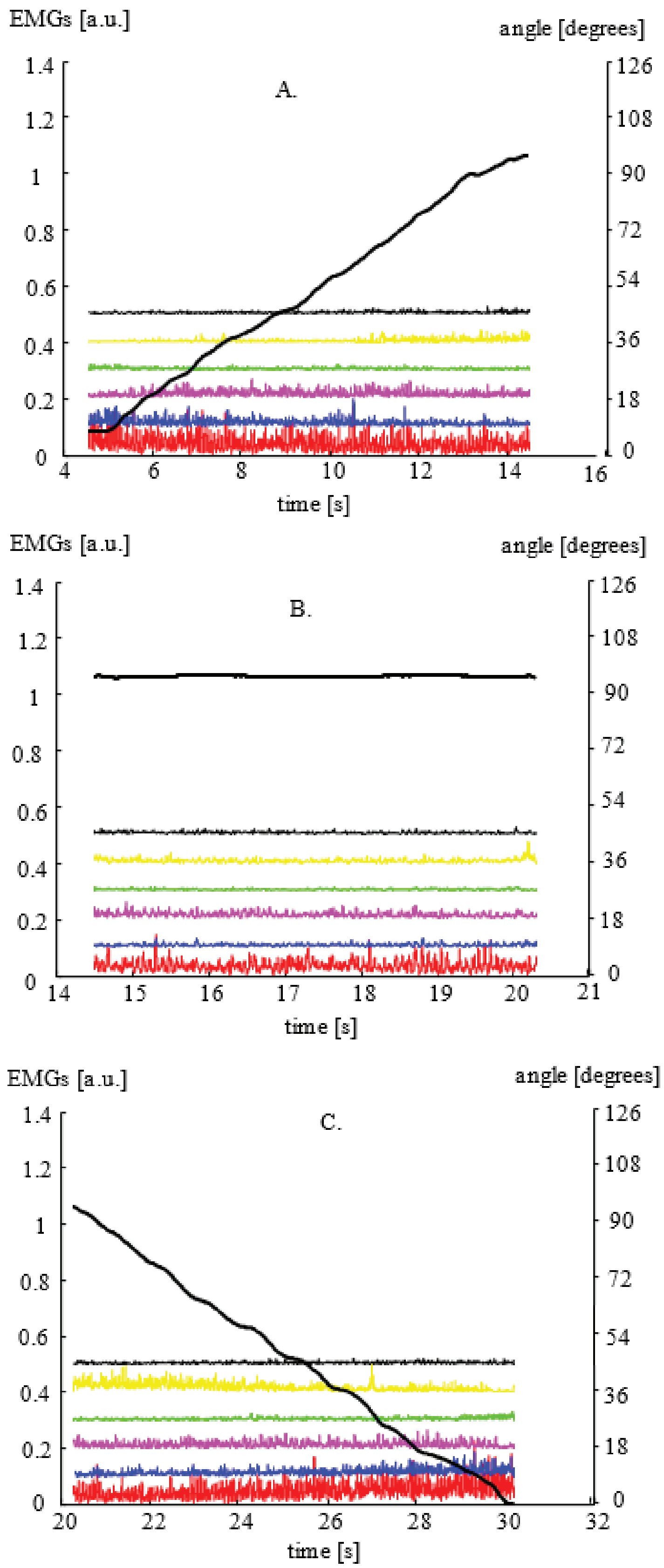

Figure 3. The chosen movement in the horizontal plane with 1st velocity, subject №4. A. The chosen flexion. B. Rest. C. Extension. The black bold line is the measured angle. The processed EMGs are coloured as follows: DELcla – red; DELspi – blue; BIC – magenta; TRI – green; ANC – yellow; BRA – black. The EMGs are filtered, normalized, rectified, and smoothed. For better visualization, each successive EMGs of the muscle is shifted up by 0.1. a.u. (arbitrary unit)

Results

Of all 15 investigated subjects, five were excluded from the statistical analysis for various reasons: large amounts of noise because of movement artefacts, many outliers, the imprecise performance of full flexion and extension, peeling off the electrodes, no smooth angle course, and cable movements. The mean angle velocity was calculated for all flexion and extension motions for all subjects as follows: $V = (\varphi_{start} - \varphi_{end})/(t_{start} - t_{end})$ (see Figs. 2A and 2C), where (start) and (end) are the respective values of the angle and time at the beginning and end of the cycle. The average velocities for all subjects are shown in Fig. 4. In general, the angular velocity was higher for movements without additional weight – mean 68.44 degrees/s for flexion and extension in the sagittal plane, and 43.63 degrees/s for flexion and extension in the horizontal plane without weight comprised with those with weight, namely: 58.49 degrees/s for flexion and extension in the sagittal plane and 41.47 degrees/s for flexion and extension in the horizontal plane.

Sagittal flexion velocity was higher than horizontal flexion velocity (for example, mean velocity for the sagittal plane without weight was 63.73 degrees/s and for the horizontal plane it was 42.45 degrees/s). The same is true for the sagittal extension velocity. The maximal value of the angle velocity was 151.1046 degrees/s during sagittal extension without an additional load during the fastest movement velocity. The minimal value was 10.0674 degrees/s during a horizontal extension with the first movement velocity without load. In general, flexion movement angles were smoother than extension movement angles (Fig. 2A and C versus Fig. 3 B, A and C – black bold lines). Here, in the figures, we use arbitrary units (a.u) instead of the original units (μV), since the data for EMGs are filtered and normalized.

The mean EMGs for all investigated subjects for all 6 muscles during motor tasks in the sagittal plane are given in Fig. 5. The profiles of the muscle activity are similar. The muscles DELspi and TRI show fewer activities independently of the movement velocities (the mean value for DELspi for flexion without weight was 4.74 a.u and with weight 4.63 a.u.; the mean value for TRI for flexion without weight was 9.14 a.u. and with weight 9.48 a.u.; the mean value for DELspi for extension without weight was 4.51 a.u., and with weight 7.75 a.u.; the mean value for TRI for extension without weight was 7.74 a.u., and with weight 6.90 a.u.). Large activities show the muscles BIC and BRA during flexion and even during extension. The mean value for BIC during flexion without load was 27.97 a.u. and with load 31.66 a.u.; during extension without load it was 12.15 a.u., and with load 15.89 a.u. The mean value for BRA during flexion without load was 38.31 a.u, and with load 42.63 a.u.; during extension with load 17.36 a.u., without load 25.27 a.u. The presence of an additional load slightly increased the activity of muscles DELcla (from 17.37 a.u. without load to 23.64 a.u. with load), BIC (from 16.00 a.u. to 21.11 a.u. and BRA (from 22.21 a.u. to 29.41 a.u.) during the flexion phase concerning the slowest motion velocities. During the rest phase, when the forearm rests in the maximally flexed position, the muscles DELcla, BIC, ANC and BRA act synchronously, resulting in no motion (they support the limb). The activity of m. BRA is comparable to that of m. BIC. Even during many of the cases shown in Fig. 5 the activity of m. BRA was higher than that of m. BIC (mean values for the four speeds: BRA – flexion without load 38.31 a.u., with load 42.63 a.u. and BIC – flexion without load 27.97 a.u., with load – 31.66 a.u.). To our surprise, the small m. ANC had high activity for all cases and task parts (during extension in the sagittal plane from slowest to fastest task without load its activity was: 30.9262 a.u. (V_1), 32.69 a.u.

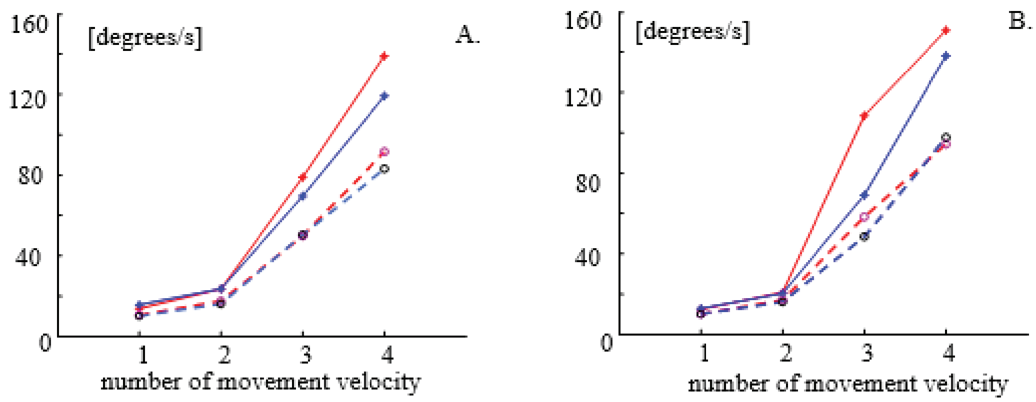

Figure 4. The mean value of the angle velocity in the elbow in degrees per second during different motor tasks. 1 indicates the slowest velocity, and 4 indicates the fastest velocity. A. Flexion; red (*) – sagittal plane; blue (*) – sagittal plane with weight; red dashed (o) – horizontal plane; blue dashed (o) – horizontal plane with weight. B. Extension: red (*) – sagittal plane; blue (*) – sagittal plane with weight; red dashed (o) – horizontal plane; blue dashed (o) – horizontal plane with weight

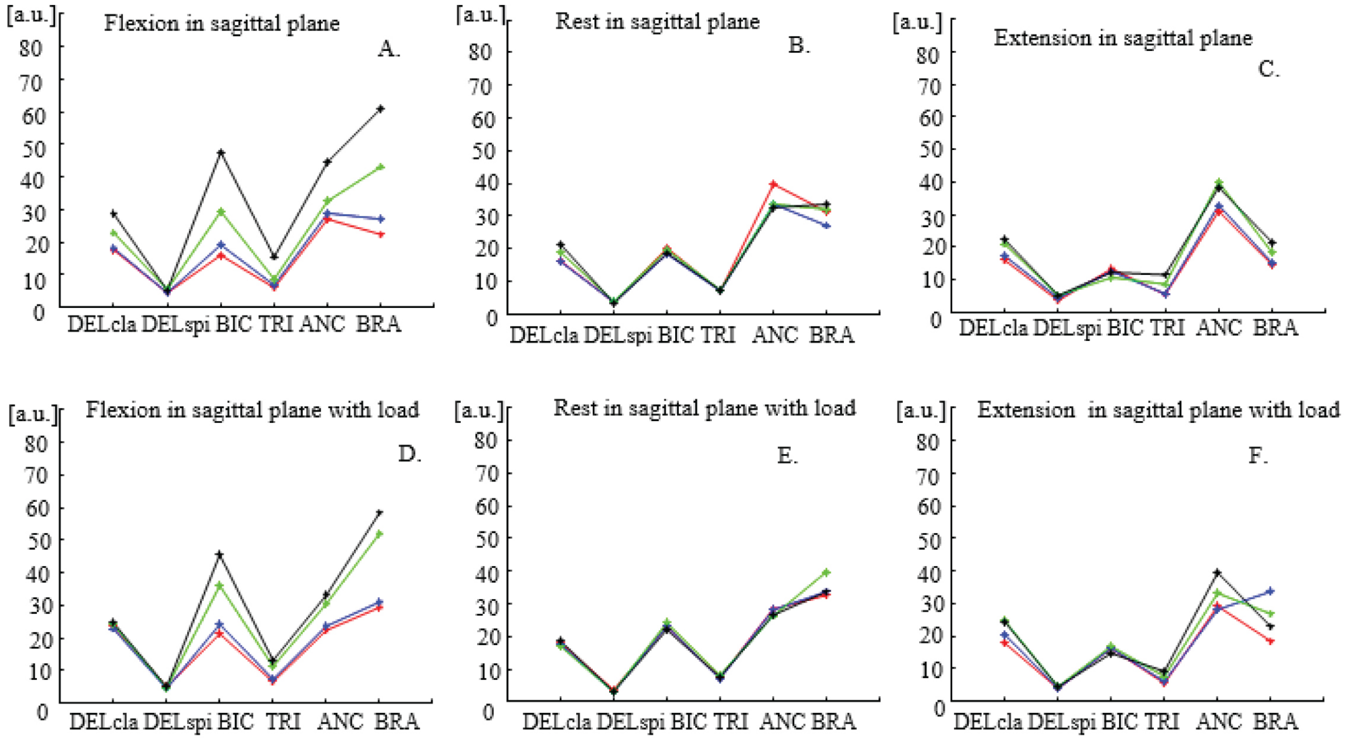

Figure 5. Mean EMG activity of the 6 muscles of all experimental subjects during movement tasks in the sagittal plane. A. Flexion; B. Rest; C. Extension; D. Flexion with load; E. Rest with load; F. Extension with load. Different colours indicate different velocities: 1st velocity – red; 2nd velocity – blue, 3rd velocity – green; 4th velocity – black. a.u. – arbitrary unit

(V_2), 39.98 a.u. (V_3), 38.33 a.u. (V_4); and with load: 29.09 a.u. (V_1), 27.99 a.u. (V_2), 33.08 a.u. (V_3), 39.34 a.u. (V_4)), which in most cases was larger than that of the other large extensor muscle TRI – its activity during extension in the sagittal plane from slowest to fastest task without load was: 5.49 a.u. (V_1), 5.68 a.u. (V_2), 8.49 a.u. (V_3), 11.32 a.u. (V_4); and with load: 5.29 a.u. (V_1), 5.89 a.u. (V_2), 7.42 a.u. (V_3), 9.02 a.u. (V_4).

In general, the activities of the investigated muscles during experimental tasks in the horizontal plane were higher (Fig. 6). Even m. DElspi showed considerable activity. Some of the muscles not only perform the motions but also support the upper limb in the horizontal plane. This support is clearly seen in m. DELcla, whose activity was very high (the measured mean value of its activity for all four speeds for flexion without load was 51.28 a.u., and with load 58.65 a.u.) in comparison with the exercises in the sagittal plane (the calculated mean value for all the four speeds for flexion without load was 21.68 a.u., and with load 23.81 a.u.). This activity was preserved for all three phases of the motor task. Here, the activity of m. BIC (mean value for four velocities for flexion without load was 35.45 a.u., with load 48.67 a.u.) was higher than that of m. BRA (mean value for four velocities for flexion without load was 15.12 a.u., with load 19.89 a.u.), perhaps because m. BIC is a biarticular muscle and participates in the support of shoulder stability. The small m. ANC showed very high activity during extension in the horizontal plane for all extension velocities (mean value 54.73 a.u. without load, and with load 60.10 a.u.).

The configuration of muscle activity during the resting phase (Figs. 5B, 5E, 6B and 6E) did not change because of the weight placement in both the sagittal and horizontal planes. Having half of a kilogram of weight at the wrist resulted in only a slight increase in m. BRA activity (mean value for the four speeds velocities increased from 30.94 a.u. to 34.75 a.u.) and a slight decrease in m. ANC activity, which was visible in sagittal plane tasks (mean value for the four speeds velocities decreased from 34.78 a.u. to 27.19 a.u.).

To investigate the influence of the motion velocity on the muscle activity for individual subjects for all muscles for each motion (flexion and extension in the sagittal and horizontal plane without and with load), figures of these dependencies were shown (in Fig. 7 only those muscles whose activity visibly changed are shown). The intervals between the four velocities, V_1, V_2, V_3 and V_4, were different, since the instructions to the subjects were to perform flexion (extension) for 10, 6, 2 and 1 seconds consecutively. For all motions, the dependencies of the activities of all 6 muscles on the velocities (not shown by figures) were summarized. It has to be noted that the authors resumed established shoulder and elbow muscle interactions during elbow flexion in the sagittal plane using the

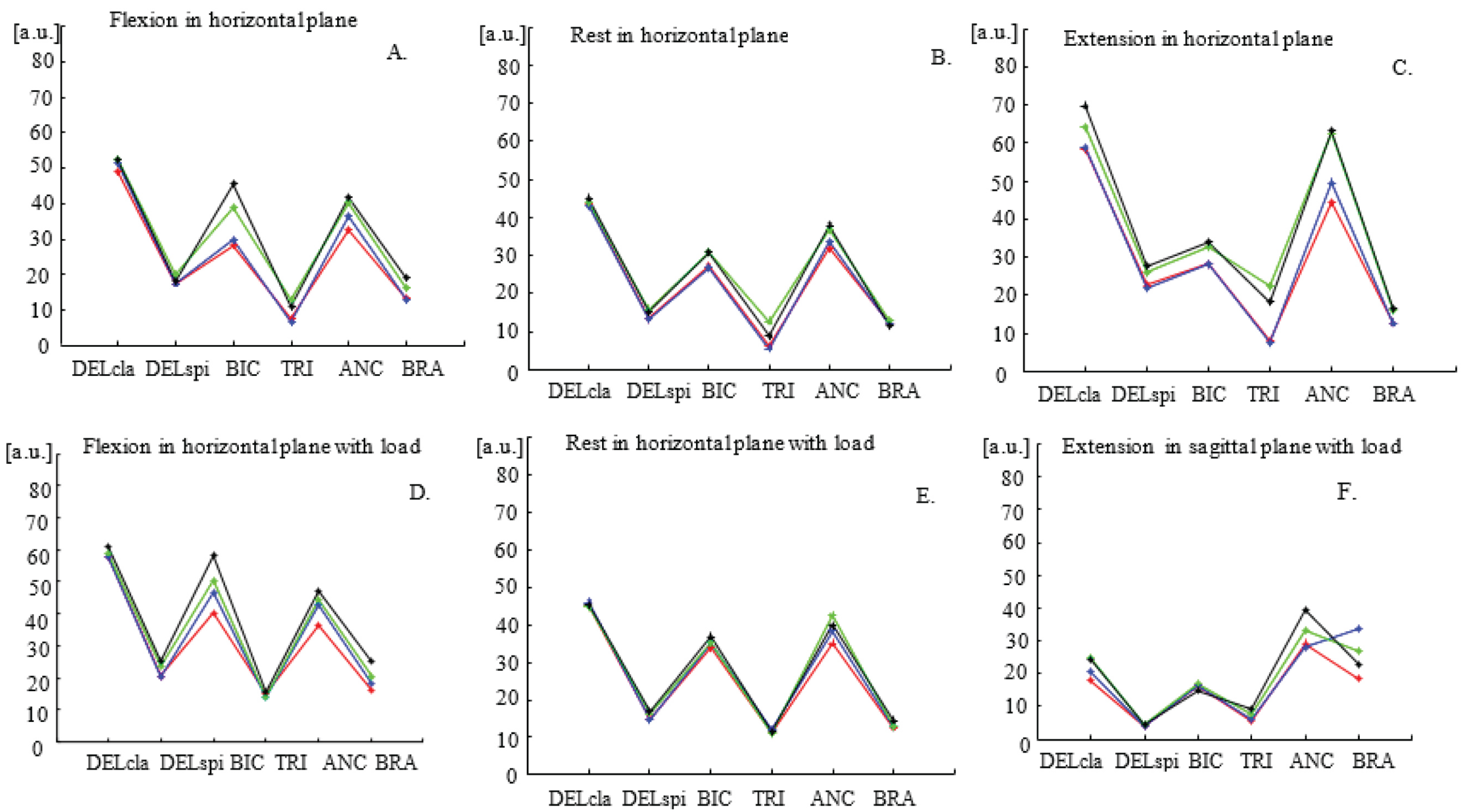

Figure 6. Mean EMG activity of the 6 muscles of all experimental subjects during movement tasks in the horizontal plane. A. Flexion; B. Rest; C. Extension; D. Flexion with load; E. Rest with load; F. Extension with load. Different colours indicate different velocities: 1st velocity – red; 2nd velocity – blue, 3rd velocity – green; 4th velocity – black. a.u. – arbitrary unit

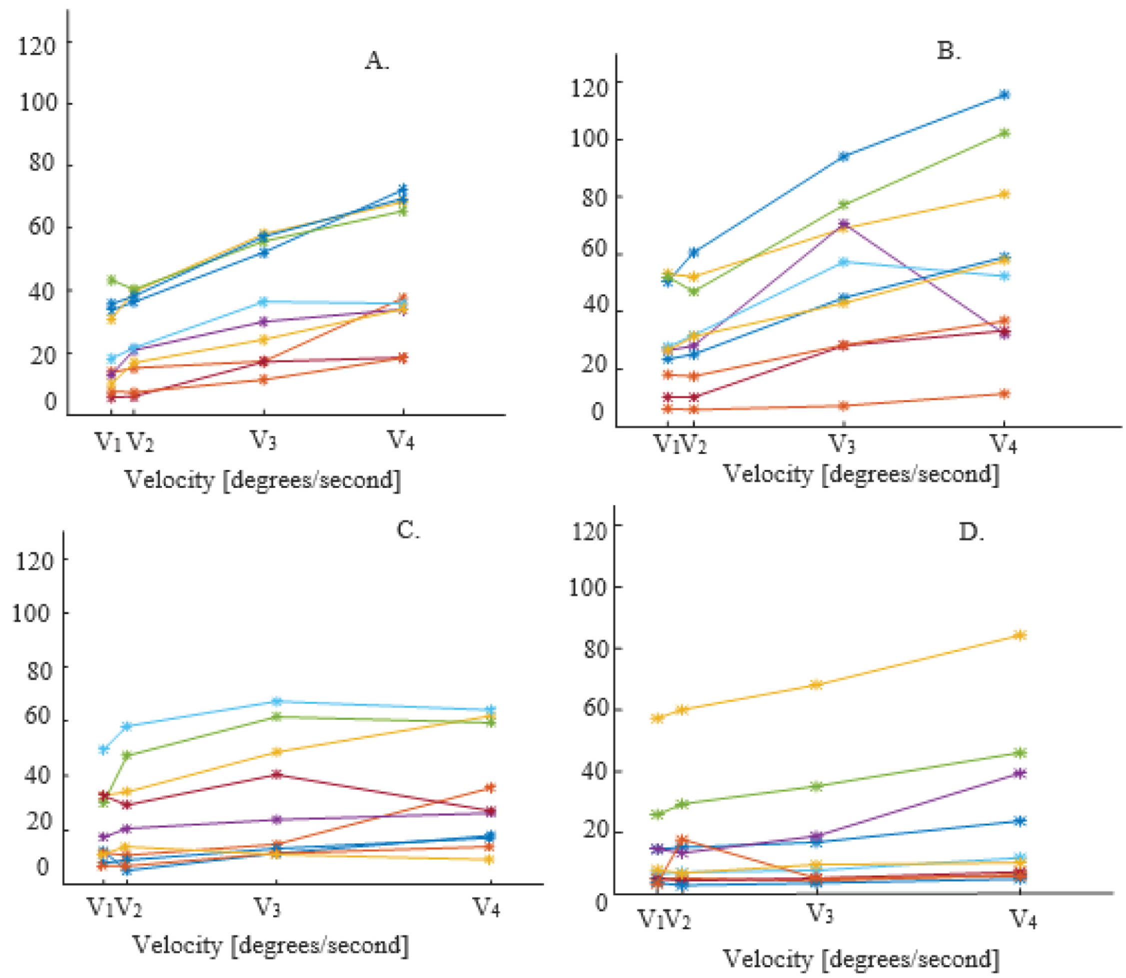

Figure 7. Dependencies of some muscle activities on the velocities. A. m. BIC – flexion in the sagittal plane with load; B. m. BRA – flexion in the sagittal plane with load; C. m. ANC – extension in the sagittal plane with load; D. m. TRI – extension in the horizontal plane with load. V_1 – first velocity, V_2 – second velocity, V_3 – third velocity, V_4 – fourth velocity. Different colours represent different subjects. a.u. – arbitrary unit

recently developed InterCriteria Analysis (ICrA) based on index matrices and intuitionistic fuzzy sets, described by Angelova et al. [3]. Additionally, correlation coefficients (CorCo) between the four mean velocities and muscle activities were calculated (an example is given in Table 1). Inspections of the figures and the values of all calculated CorCo yield several general conclusions. The muscle ANC was used by subjects in very different ways (Fig. 7C) and was very active, including during flexion (Fig. 5A) (the anatomical literature defines this muscle as an extensor). It was less active during flexion in the sagittal plane and most active (sometimes, for some subjects, its activity exceeded 100%, especially during extension in the horizontal plane with the 4th velocity). Its activity did not increase with increasing weight. In most cases, it was more active than m. TRI. The activity of m. TRI, independent of its low activity, surprisingly increased with velocity (Fig. 7D and Table 1), with CorCo for flexion in the sagittal plane with load being very high for all subjects (mean CorCo is 0.93). For some subjects, its activity in the horizontal plane (Fig. 7D) was very small, even though here it is the main extensor, and the moment of gravity is constant. The muscle BIC increased its activity with velocity during flexion (15.99 a.u. (V_1), 18.99 a.u. (V_2), 29.28 a.u. (V_3), 47.59 a.u. (V_4)) (Fig. 7A), but its activity was nearly constant during extension, which was more visible in the sagittal plane than in the horizontal plane. The same is valid for m. BRA (Fig. 7B). The activities of these two muscles – BIC and BRA – were very similar in all cases. The muscle DELspi was barely active in sagittal motion but was twice as active in the horizontal plane, and its activity did not depend on the motion velocity. The muscle DELcla showed very different behaviour for different subjects. In most cases, its activity increased with velocity for both flexion and extension.

The addition of weight did not significantly change muscle activities during motions of flexion in the sagittal plane. The muscles BIC and BRA were most active, and their activity increased with increasing velocity. The muscle DELcla was less active, but its activity also increased

Table 1. Correlation coefficients (CorCo) between the activity of the respective muscles and the mean velocities. Motor task: flexion in the sagittal plane with load. CorCo with absolute values less than 0.5 are marked in red

MUSCLE	SUB1	SUB2	SUB3	SUB4	SUB5	SUB6	SUB7	SUB8	SUB9	SUB10
DELcla	–0.5902	0.8877	0.4651	0.5747	–0.7738	0.8670	–0.2913	0.9954	–0.4631	–0.1983
DELspi	–0.6736	0.8001	0.2939	0.6961	–0.8707	0.4306	0.8385	0.9358	–0.7247	0.2818
BIC	0.9991	0.9217	0.9733	0.9315	0.9808	0.8933	0.9364	0.9927	0.9838	0.979
TRI	0.9963	0.8977	0.9884	0.9237	0.7976	0.8060	0.9834	0.9986	0.9951	0.9383
ANC	0.7805	0.9261	0.9991	0.9511	0.7944	0.7533	–0.1589	0.9983	0.9866	–0.7552
BRA	0.9879	0.9463	0.9924	0.2844	0.9884	0.8383	0.9644	0.9957	0.9943	0.9970

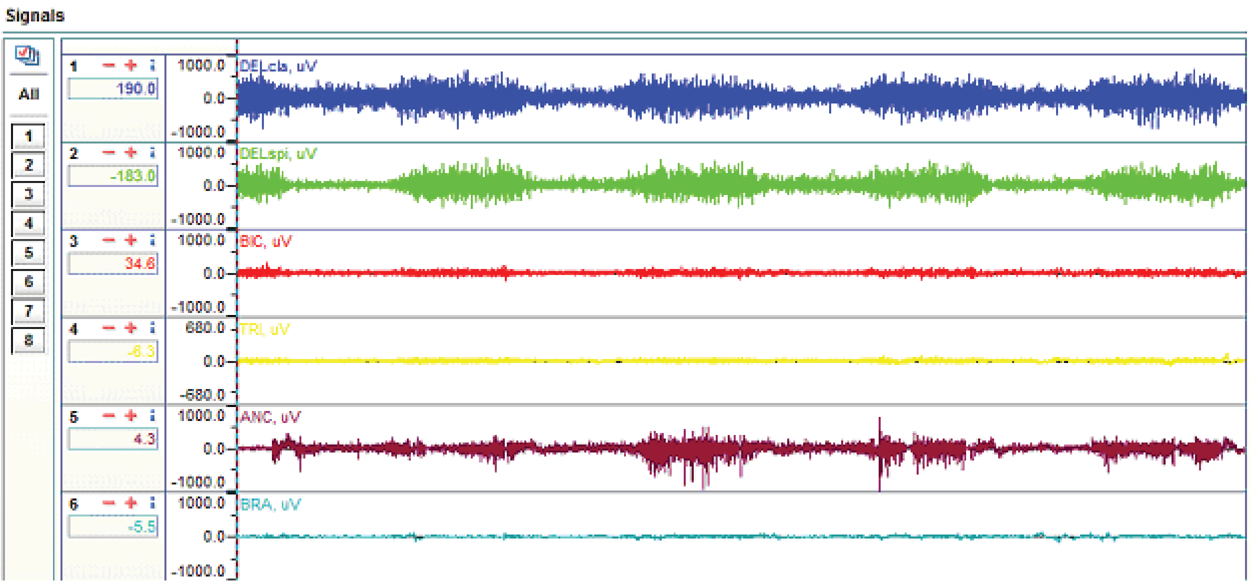

Figure 8. Screenshot from the Noraxon program showing the original signal of all 6 muscles. Motor task – horizontal flexion/rest/extension with additional load, 3rd velocity. The original EMG signal of m. ANC in μV is higher than that of m.TRI

with velocity. The muscles DELspi and TRI were barely active. To our surprise, the small m. ANC showed considerable activity during extension phases: the mean value for the four speeds was 35.48 a.u. (for different velocities the values were as follows: V_1 – 30.93 a.u., V_2 – 32.69 a.u., V_3 – 39.98 a.u., V_4 – 38.33 a.u.), and this activity increased with increasing motion velocity.

For the extension motion, m. DELspi was not active, whereas m. DELcla and m. BIC exhibited nearly constant activity for all velocities. The activity of m. BRA slightly increased (for different velocities it was as follows: V_1 – 14.73 a.u., V_2 – 15.13 a.u., V_3 – 15.13 a.u., V_4 – 21.42 a.u.), during extension, although this muscle is a flexor. The activity of m. TRI was low (mean value for flexion for the four speeds without weight was 9.14 a.u., and for the extension phase 7.75 a.u.), whereas the small m. ANC reached 80% of its activity during motions with maximal velocity.

Discussion and conclusions

One highlight of this study is the investigation of the electromyographic activity of two flexors and two extensors in the elbow joint. In each direction, we investigated two biarticular muscles – BIC and TRI caput longum. However, the one-joint elbow muscles – ANC and BRA – are located in semi-accessible locations, and obtaining their EMGs is challenging. The m. BRA lies under m. BIC on the anterior side of the os humerus. Some authors think that it cannot be studied using surface electromyography [5, 26]. Although a very small part of m. BRA is on the surface, Date et al. [10] proved that its activity can be assessed using surface EMG, similar to other surface muscles. Specifically, they found that the EMG patterns of m. BRA activity were not significantly different when recorded using surface and fine-wire electrodes during elbow flexion.

One of the difficulties in this study was cross-talk, which appeared when the muscles close to each other were active simultaneously [11]. This phenomenon was probably present for the m. BRA in some volunteers. EMG recordings can be inferred from the neighbouring active muscle concerning m. BIC and m. ANC. The muscle ANC is closely suited to the extensor digitorum and extensor carpi ulnaris muscles and tendons of several other muscles attached to the epicondylus lateralis. This phenomenon could explain the high activity of m. ANC.

In addition to EMG signal access using small electrodes, another uncertainty concerning m. ANC is its function, which has not yet been elucidated. This muscle has been suggested to be an elbow extensor, while other researchers suggest that its action is associated with the abduction of the ulna. Miguel-Andres et al. [21] write that m. ANC is a weak extensor and does not significantly contribute to elbow kinematics. However, as mentioned in this paper, m. ANC is an important secondary stabilizer of the elbow. It is also visible in the figures presented by Miguel-Andres et al. [21], showing that the normalized EMG activity of the m. ANC is higher than that of m. TRI during all movements. Other authors also believe that m. ANC contributes to the dynamic stabilization of the joint.

The muscles that cross the joint capsule can be considered stabilizers. Through their contraction, they compress the joint. O'Driscoll et al. [24] hypothesized that m. ANC, along with the muscles TRI and BRA, stabilizes the elbow joint. Another study [32] found a connection between the muscles TRI and ANC. They proposed that m. ANC is a continuation of the lateral head of the m. TRI, and thus its role as a dynamic stabilizer is defined. According to a previous investigation [3], ICrA detected muscle pair TRI-ANC consonance (consonance is considered as existing muscle interaction of these two muscles) during flexion in the sagittal plane for 4 out of 10 subjects and during extension in the sagittal plane for 3 out of 10 subjects.

Our investigations showed that m. ANC could be assumed to be a definite prominent extensor because its activity is considerable. Even if the maximal isometric force was not appropriately recorded for some subjects, this could not have happened for all subjects. Even in raw, unprocessed data (Fig. 8), the high EMG activity of m. ANC is visible. Note that in our statistics and figures, the EMGs are normalized. This does not mean that m. ANC develops more force than m. TRI; rather, it develops a larger percentage of its maximal measured force. Conversely, Fig. 2 and Fig. 3 show that its activity remains high both during maintaining the resting position of the arm and during flexion. Therefore, m. ANC can also be assumed to act as a dynamic and static stabilizer.

Travill's study [34] examined the activity of the three heads of the m. TRI and m. ANC during elbow flexion and extension in four different shoulder joint positions with and without resistance. Here, "negligible" or "no" activity was observed from the long head of m. TRI during the majority of the non-resisted movements. Thus, they concluded that the medial head of m. TRI, rather than the combined medial and lateral heads of m. TRI, is the prime mover during elbow extension. Consequently, we may not see significant activity from the investigated long head of m. TRI – it is less powerful during elbow extension. In addition, the author claims that during free extension of the elbow, m. ANC is more active than the long head of m. TRI in most of their recordings. We observed the same phenomenon during free extension and extension when 0.5 kg was attached to the wrist.

Andres [2] recorded the electrical activity of the muscles ANC, BIC and TRI during flexion and extension while standing. Constant m. BIC activity was clearly evident, and Appendix 3 in the mentioned paper shows that m. ANC was significantly active. In our analogous Fig. 2, we also show m. BIC activity during all phases of the movement; m.TRI activity was weak and m. ANC was acting significantly, as previously mentioned. The relation of BIC-TRI antagonists' activity was investigated using the ICrA method by Algelova et al. [3] and was proved in eight of ten subjects. The same method found the BIC-BRA relation of nine out of ten subjects during elbow flexion in the sagittal plane. Caufriez et al. [8] described additional observations: at the end of elbow flexion, m. BIC and m. BRA are less efficient for elbow flexion. They found increased electromyographic activity of m. BIC during resisted elbow flexion with the forearm supinated with a peak at 57.1° elbow flexion and observed that the forearm position did not influence the muscle activity of m. BRA. Our Fig. 2A shows similar results: m. BIC is more active from the beginning of flexion to the middle of the movement, which is approximately the degrees mentioned.

Notably, the data shown in Fig. 5 and Fig. 6 are mean values of the normalized EMG activities of all muscles. Therefore, no absolute value of the signal is given, but the percentage of maximal isometric activity. In general, the m. DELspi and m. TRI have little activity in all movement tasks, which is to be expected for m. DELspi. However, the activity of the main elbow extensor, m. TRI, was expected to increase during extension, especially in the horizontal plane. Instead, the activity of the small m. ANC increased considerably (Fig. 6C and 6F). This finding can be explained as follows: we recorded the activity of the biarticular part of m. TRI, which also extends the shoulder and likely adds more effort to this joint.

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