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Identification of muscle movements and activity by experimental methods for selected cases – stage #2

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Purpose: The aim of the performed tests and static measurements was to determine the torque and to determine the activity curve for individual muscle heads during the flexion-extension movement in the elbow joint. *Methods*: Both heads of the biceps branchial muscle and the triceps muscle of the arm – long head and lateral head – were examined. Static measurements were carried out for four selected positions of the upper limb. For each pose, a measurement series consisting of five attempts of ten seconds of effort was performed. Isometric contraction was performed as 100% of the maximum voluntary MVC contraction. Dynamic measurements were carried out when working in isokinetic conditions. In both stages, an EMG and a Biodex isokinetic dynamometer were used. *Results*: During the analyses, it was assumed that the average value of the torque is equal to the approximate value of the torque of a given head under static conditions. The value of the torque of the biceps brachial muscle, long head was 48.04 Nm and for the short head – 45.82 Nm. For the triceps muscle of the long head, this value was 52.52 Nm and for the lateral head – 38.06 Nm. On the basis of dynamic measurements, four activation curves were determined for each of the heads during the 7-second task. For the curves, the sum value of muscle activity in a given period of time was calculated as the area under the curve. *Conclusions*: Both parts of the series of articles present a series of experimental studies conducted in order to determine the parameters for one patient, for whom a personalized numerical model of the upper limb was ultimately created. Static measurements were carried out to determine the maximum values of the moments of forces. Dynamic measurements allowed for the determination of activity curves during the movement of the upper limb.

Key words: *EMG, Biodex, MVC, muscle activity*

1. Introduction

Muscle momentum is one of the parameters that determine muscle performance. Strength measurements are used to assess physical condition, weakness related to illness or old age and are used to monitor the progress of rehabilitation. Tests in static and dynamic conditions are widely used in clinical and academic activities [2]. There are publications in which the moments of muscle strength have been studied in static conditions, thus enabling a diagnosis or setting the direction of further research. One of the examples may be paper [13], where the moment of strength of the hip and knee muscles was compared between people after an ankle joint injury due to sprain and healthy people. Studies have shown a lower torque during joint flexion and extension among people with a history of ankle sprain. Strength deficits, in turn, are associated with reduced posterolateral balance capacity. The data suggest that torque assessment is important in treating sprains. The authors [30] searched for links between the functional asymmetry of the lower limbs and the maximum moments of strength of the ankle joint among men and women. Measurements included isometric contraction at one flexion angle. The obtained results confirmed the lack of correlation between the functional dominance of the limb and greater muscle strength, regardless of the gender of the examined person. The torque parameter is also widely used in sports. An example may be the article [18], where the moments of strength between the athletes of taekwondo and boxing were compared. On the basis of measure-

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ments made in static conditions, it was found that, among others, taekwondo players achieved much higher absolute torque values for the elbow flexors, extensors and shoulder flexors than boxers.

It is well known that the values of torque generated during isometric contractions depend on the angle of flexion at the joint, with peaks typically found in the middle of the range of motion. However, it depends on muscles, gender or individual characteristics [20]. In order to more reliably check the efficiency of muscle fibre recruitment, measurements of the generated muscle forces at specific angles of flexion in the joints during isometric effort are often combined with the measurement of muscle activity using EMG electromyography. In paper [20], measurements of the torque and muscle activity were performed for the extensors of the knee joint at six different flexion angles during isometric contraction. The results indicated higher values of the torque generated by men with the determination of the angle at which it occurs. Research shows angle-specific and gender-specific torque responses, while EMG-determined motor unit recruitment was greatest at one angle and less gender-dependent. The authors of the publication [31] also focused on the knee joint and put forward the thesis that the deficiencies in the knee extensor torque accompany the disorders of muscle activation among patients with knee arthrosis. The thesis was confirmed on the basis of the recorded muscle activity and the torque. The research on the knee and ankle joint was also presented in the publication [7], where the influence of the aging effect and past injuries on the ability to develop the torque in women was examined. This assessment was possible through the simultaneous use of an EMG and an isokinetic dynamometer, and the results of the research showed that women after injuries had a lower ability to generate the maximum torque and slowed recruitment of muscle fibres. The conducted tests confirmed the strong influence of aging on the ability to react quickly during a fall and provide initial exercise recommendations in rehabilitation programs.

Isokinetic dynamometers allow for the quantitative assessment of dynamic muscle contraction by controlling the speed of movement, resistance and the position of the tested body part. Isokinetic studies are widely used during strengthening exercises in the assessment of the muscle strength in the sick [12], [14] and the healthy people [6], [8], [29], and in muscle performance tests among the athletes [33]. An example of the use of isokinetics can be found in the publications [15], [16], [26], where the contribution of the quadriceps heads in the generation of torque in people with patellofemoral pain syndrome was assessed. The assessment was performed using concentric tests performed at different speeds of flexion and extension, and with the use of EMG sensors. Conducting such studies made it possible to conclude that there are significant differences between sick and healthy patients in terms of the share of individual muscle heads. It was also found that exercises of concentric contractions at different speeds should be included in the rehabilitation process. Age-related muscle weakness was presented in [10], where men of various age groups were tested with the use of a dynamometer and EMG sensors. Older people were characterized by a lower torque both at low and high angular velocities. In [22], isokinetic and electromyographic fatigue among tennis players was analysed. The analysis showed that the induced fatigue was mainly peripheral and resulted from metabolic and ionic changes. The aim of the article [32] was to investigate the reliability of muscles during the maximum isokinetic flexion and extension of the shoulder. The performed measurements of the torque as well as the EMG signal allowed us to conclude that the application of the maximum load is a promising approach to the assessment of pathological changes. The authors of paper [3] investigated changes in muscle activation and the maximum torque load during an isokinetic task at a given angular velocity in people with and without chronic back pain. The patients showed variable and less efficient activity of the spine muscles.

This publication presents measurements for the static and dynamic range of functioning of the biceps and triceps muscles. The aim of the first measurements was to determine the torque under static conditions. The determined torque is to be used in analytical calculations to estimate the maximum isometric force, optimal length and physiological cross-sectional area. This parameter is necessary to describe the functioning of the muscles. The aim of dynamic measurements was, however, to determine the activity curve in the range values of 0–1 for individual muscle heads during the flexion movement, i.e., during extension of the upper limb at the elbow joint. The parameters obtained in both tests may serve as input data to be implemented in the Hill constitutive model in order to map the functioning of the numerically described biceps and triceps muscle.

2. Materials and methods

2.1. Object of interest

The subjects of our research, as in the first part of this series of articles, are the two largest muscles in the arm, the biceps muscle of the shoulder and the triceps muscle of the arm. Heads located directly under the skin were examined. In the case of the biceps muscle, these are both heads, i.e., the long head and the short head, while for the triceps muscle, two superficial heads, i.e., the long head and the lateral head, were examined. The biceps muscle of the shoulder acts as a flexor, while the triceps muscle of the arm as an extensor in the elbow joint [4].

All measurements are personalized for a man aged 35, with a height of 182 cm and weight of approx. 72 kg. The volume of the biceps brachii in a given individual is 277.869 mm^3, and the volume of the triceps brachii is 567.409 mm^3. The volumetric values were determined on the basis of the performed magnetic resonance imaging.

2.2. Experimental protocol

The research in this study was divided into two stages. In the first stage, measurements were made for the static work of the muscle, and in the second one, they focused on measurements during the dynamic work of the muscle.

The first stage was based on the measurements presented in the first part of the series of articles [9], where the positions of the upper limb were checked in order to determine the most activating and isolating position for individual muscle heads. On the basis of these studies, four positions were selected with the highest activity of the four analysed muscle heads.

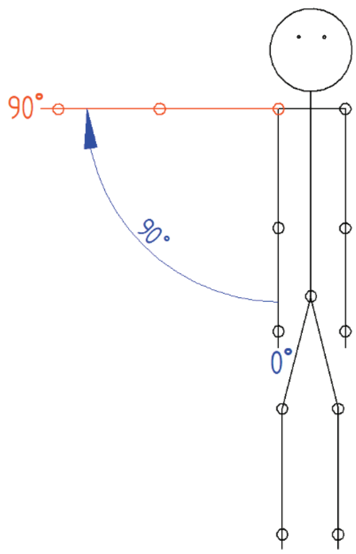

Fig. 1. Abduction in the shoulder joint (frontal plane)

For the long head of the biceps muscle, 90° shoulder abduction was selected (Fig. 1). The short head of the biceps brachii was characterized by the greatest activity when flexing at the elbow joint at an angle of 115° (Fig. 2). The long head of the triceps muscle of the shoulder reached the greatest activity during the straightening task in the shoulder joint at an angle of 30° (Fig. 3), and the position selected for the lateral head of the triceps muscle of the shoulder was the elbow extension at an angle of 115° (Fig. 4).

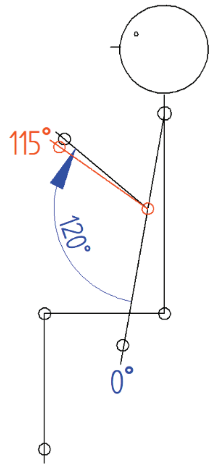

Fig. 2. Bending in the elbow joint in a sitting position (sagittal plane)

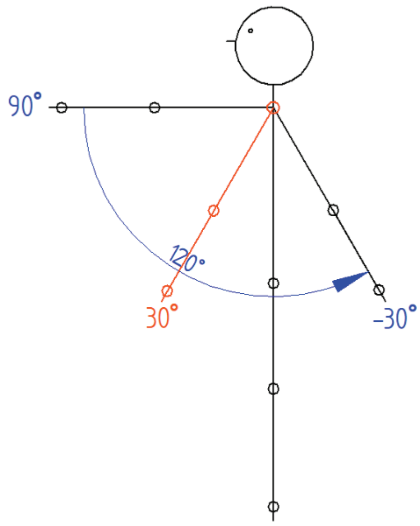

Fig. 3. Straightening in the shoulder joint (sagittal plane)

The isometric contraction was again measured for the four positions shown. For each pose, a measurement series consisting of five attempts of ten seconds of effort was performed. After each 10-second effort, muscle recovery time was 3 minutes, avoiding muscle fatigue. Isometric contraction was performed as 100% of the maximum voluntary MVC contraction. The aim of the first stage was to determine the approximate values of the moments of strength of individual muscle heads in the indicated/analysed movements. The determined values of the moments of force were used in analytical calculations.

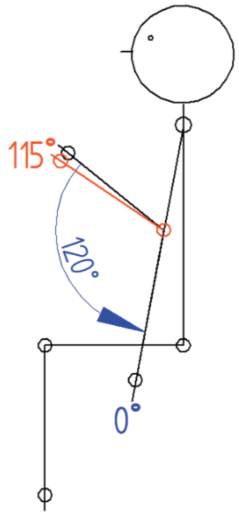

Fig. 4. Straightening in the elbow joint (sagittal plane)

The second stage of the research was carried out for muscles working in isokinetic conditions characterized by a constant speed of movement. The measurement included extension and flexion movement in the elbow joint at a speed of 45 °/s = 0.79 rad/s. The value of the set speed was chosen based on the patient's assessment as the speed closest to the actual movement and at the same time characterized by optimal resistance and comfort during the measurement. A measuring series consisting of five repetitions was carried out. The aim of the second stage of the research was to determine the activity curves of individual muscle heads during the analysed upper limb movement, for which target numerical analyses will be carried out.

2.3. Data recording

Experimental studies were carried out on a 35-year--old man with no known musculoskeletal problems in the upper limb.

In the first part of the study, in order to determine muscle activation, an electromyograph was used, which allows for non-invasive measurement of superficial muscle stimulation, and an isokinetic dynamometer to measure torque in the axes of the elbow and brachial joints depending on the analysed upper limb position.

In the second part of the study, an electromyograph was used to record muscle activity, while an isokinetic dynamometer was used to give a constant speed of movement and stabilize the entire body and limbs.

The measurements were carried out on the sEMG by Noraxon from the USA with a built-in bandpass filter for the frequency of 10–500 Hz. Signal processing was performed with MR 3.14 software. The EMG signal was recorded with the highest available sampling frequency, i.e., 2 kHz [17]. Before sticking the measuring electrodes, the measuring site was cleaned with a disinfectant. According to the records given in the publication [11], the measuring electrodes were attached to the area of the upper part of the muscle heads, thus enabling their distinction. The isokinetic dynamometer Biodex System 4 Pro (Biodex Medical Systems, Inc., Shirley, NY, USA) was used in the research, where the signal was recorded with the highest available sampling frequency, i.e., 1 kHz.

Fig. 5. Exemplary positioning – extension of the shoulder joint at an angle of 30° – examination for the triceps muscle, long head

3. Results

3.1. Results for isometric contract

For the signal obtained in μV units, the RMS (Root Mean Square) statistical measure was used for 100 ms of the measurement, and the moving average for 100 samples was successively determined in order to smooth the measurement. The recorded torque was generated by the entire muscle group consisting of three flexors (biceps brachii, brachial muscles and coracobrachialis muscles) and extensors (triceps brachial muscles). We focused on the largest flexor and extensor of the arm and distinguishing between the heads of these muscles. In order to determine the ap-

Table 1. Summary of the results from the first stage of the research

	Shoulder abduction. Long head, biceps	Elbow joint bending. Short head, biceps	Shoulder joint straightening. Long head, triceps	Elbow joint straightening. Lateral head, triceps
Test 1 [Nm]	51.3	45.7	47.5	35.9
Test 2 [Nm]	46.1	46.2	52.1	37.7
Test 3 [Nm]	45.3	43.4	57.6	38.9
Test 4 [Nm]	49.4	44.6	50.2	38.6
Test 5 [Nm]	48.1	49.2	55.2	39.2
Mean [Nm]	**48.04**	**45.82**	**52.52**	**38.06**
Relative error [%]	13.25	13.36	21.26	9.19

proximate torque of individual heads of muscles, the time moment in which the greatest activity occurred during the dedicated tasks was compared to the corresponding time moment in the measurement of the torque recorded on the Biodex device. The procedure was repeated five times for each of the four tests, and the mean value of the torques was determined. The results are presented in Table 1. The analyses assumed that the average value of the torque is equal to the approximate value of the torque of a given muscle head.

The given mean values of the torque were used in preliminary numerical analyses to determine the maximum isometric force F_{max} and the optimal length of the muscle L_0 and the physiological cross-sectional area PCSA, i.e., parameters necessary for the implementation of the Hill constitutive model [25], [28].

3.2. Results for the isokinetic movement

In order to determine the activation curve of individual muscle heads in the value range of 0.0–1.0, the generated EMG signal was compared to the maximum activity values obtained in the tasks. The signal values were multiplied by 100 in order to obtain the waveforms in a specific range, which is characteristic of the activity curve. For the signal obtained in μV units, a statistical measure of the square mean was used to estimate the order of magnitude of a series of numerical data or a continuous function performed for the measurement time of 100 ms. Then, a moving average was determined for the 100 samples in order to smooth the measurement. The assumed movement in target numerical analyses is flexion – extension in the elbow joint. Unfortunately, programming the dynamometer meant that the measurement had to be carried out for the extension – flexion movement. In the courses presented below, the sequence of actions has been changed to flexion – extension. The procedure was repeated five times for each of the four tests, for the speed of 45°/s, and then the average course of the curves was determined on their basis (Fig. 6). The obtained curves were characterized by measurement noise and therefore for the 7-second run, local extremes were deter-

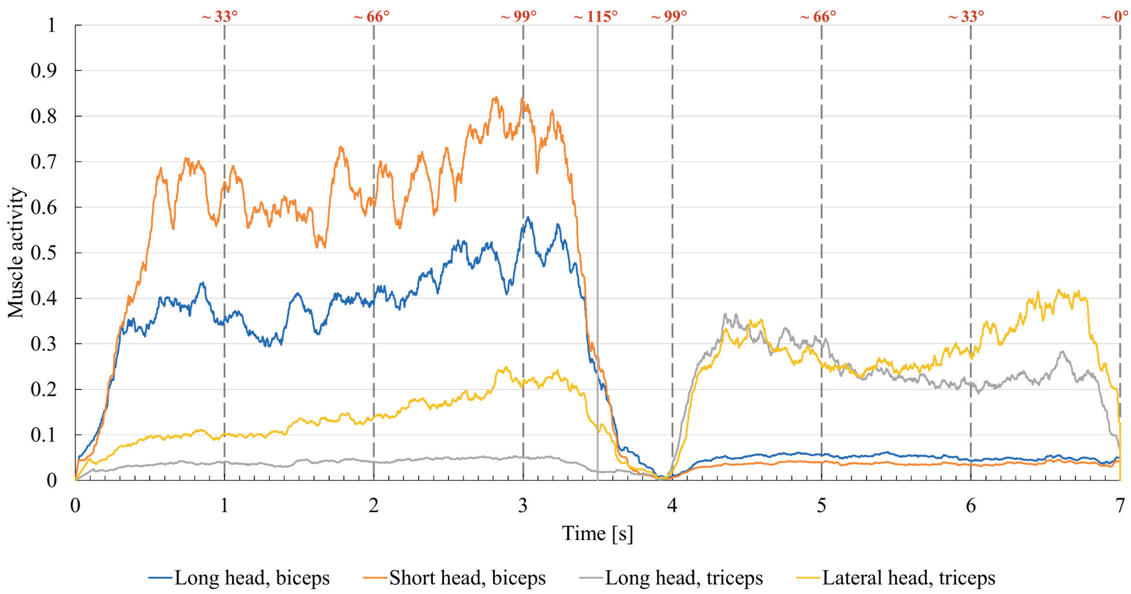

Fig. 6. Muscle activity as a function of time recorded during the tests (results before the filtration process)

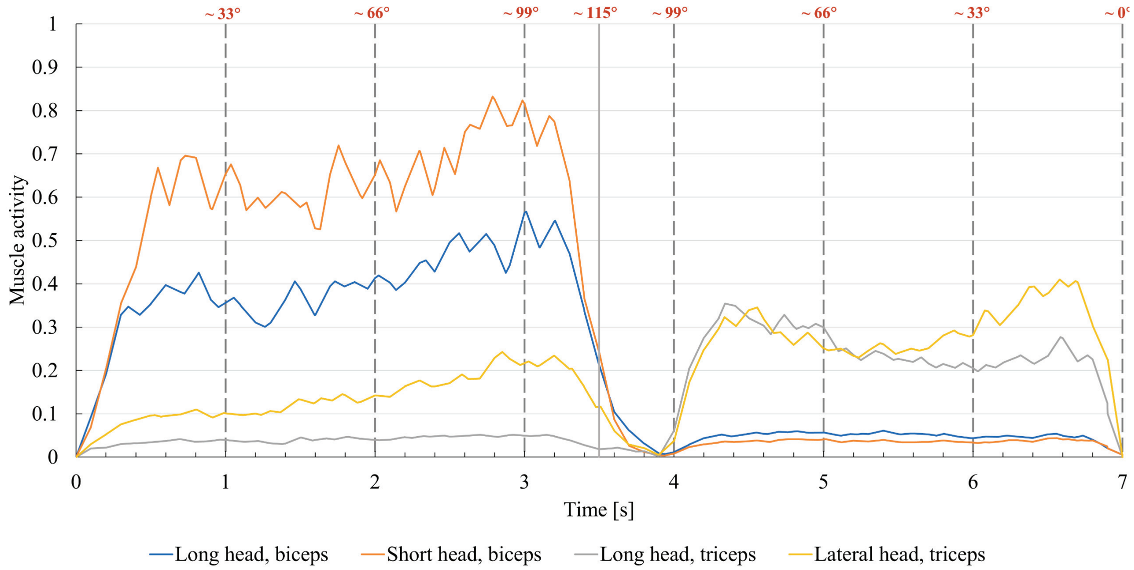

Fig. 7. Muscle activity as a function of time for 140 measurement data

Table 2. List of values of the areas under the curves

	Total value of muscle activity			
	Biceps brachii, long head	Biceps brachii, short head	Triceps brachii, long head	Triceps brachii, lateral head
Flexion t: ≤ 0.2; 3.5⟩ [s]	1.35	2.082	0.137	0.479
Extension t: ≤ 3.5; 7.0⟩ [s]	0.175	0.13	0.732	0.867

mined with a frequency of 0.1 seconds. This procedure allowed for a significant reduction in the number of measurement points (Fig. 7).

For the four curves shown in Fig. 7, the total value of muscle activity in a given period of time was calculated as the area under the curve using the trapezoidal method. The area of flexion – extension was distinguished when summing the obtained values. The obtained results are presented in Table 2.

4. Discussion

There are no methods of non-invasive measurement of muscle strength and it is not possible to directly calculate their value. Therefore, force estimates are used [27]. In the available literature, various methods of determining the value of muscle forces (used for various purposes) are presented, and they are not necessarily consistent with the method presented in this publication. Muscle strength is an important parameter in biomechanical research, e.g., due to the need to determine the load in the joints. In [19], the relationship between the EMG and the torque for two heads of the biceps brachial muscle was determined. The measurement was taken at a 90° angle in the elbow joint at three different levels of stress. The determined EMG – torque increased linearly in time from zero to the maximum value. No significant differences were detected between the muscle heads. The authors of paper [23] measured the force of the elbow flexor using a force transducer that was attached to the patient's arm at an angle of 120° flexion. The normalized RMS EMG as a function of the normalized force level in the range of 0.0–1.0 for the whole group of subjects (n = 12) was presented. The relationship was relatively linear. In two patients, the EMG-force relationship showed an inconsistency that occurred at the lower levels of contraction of 30% to 40% MVC. In the study [1], the tests were carried out on three heads of the triceps brachial muscle during the maximum voluntary contraction of isometric extension at an angle of 60°, 90° and 120° in the elbow joint. The relationship between the normalized EMG signal and the normalized force for all muscle heads was determined. The values of the EMG signals were collected at the moment of occurrence of the highest values of the force. The main relationship that the study found was that the force-EMG relationship was similar in the three muscle heads at each joint angle. Additionally, the RMS EMG of each muscle increased linearly with increasing strength. The EMG and force values are expressed in % in order to compare the results with those presented in the publication.

A small number of studies is available that summarize the maximum values of the EMG signal and the torque of the muscles of the upper limb. Against the background of the described literature examples, the series of experimental studies presented was designed for the purpose of muscle modelling using the finite element method. The target task of the research from the first stage of this study is to determine the maximum isometric forces of the heads of the biceps and triceps muscles. To obtain this parameter, numerical analyses will be based on the designated torques of individual muscle heads.

Summarizing the presented stage of research resulting from the work carried out, it should be stated that:

1. the positioning cases corresponding to the greatest activation and isolation of the four muscle heads of the upper limb were selected;
2. for selected positions and angles covering the range of motion, isometric contraction measurements were carried out during which the EMG signal was measured;
3. on the basis of the normalized EMG signals, the position and the angle of the greatest activity of each of the four heads were determined;
4. EMG and torque measurements were again carried out for the designated four arrangements. The determined value of the torque was the value at the moment of the occurrence of the greatest muscular activity of the muscle responsible for a given contraction;
5. in future works, on the basis of the determined torques, the parameters characterizing the work of individual muscle heads are to be determined.

The obtained results lead to the conclusion that, for the examined patient, the long head of the triceps brachii had the highest mean torque, and the lateral head of the triceps brachii had the lowest. The difference between the obtained values is about 38%. The values of the mean torques of the biceps brachial heads are similar, and the difference is about 5%. Higher mean values were obtained by the long head of the biceps brachial muscle.

For the constitutive Hill's model, describing the behaviour of the muscle, apart from the numerical values of the parameters, the curves characteristic for the work of the muscle are also used. One of them is the activation curve. Determining the activation profile of each of the muscle heads is possible by processing the EMG signal. Muscle activation is expressed as a number in the value range of 0.0–1.0 [5]. Infrequent use of activation curves for the upper limb results in a small number of published studies in which they were designated. The study [24] summarized the EMG in the value range of 0.0–1.0 (calling it the total EMG intensity) as a function of the elbow angle during movement at various loads (% of the maximum concentric load). The movement was in the range of 35–115° at a constant speed of 30°/s. The maximum activity value of 1.0 was reached by the biceps muscle of the shoulder during 80% of the effort near the 45° angle. In addition, regardless of the level of load, the biceps muscle of the shoulder near the 45° angle had the highest activity values during concentric movement. In the case of the upper limb, the authors [21] determined the activity patterns for four forearm muscles in the range of 0.0–1.0. The recorded surface EMG signal and its normalization to the activity curve allowed for the illustration of muscle coactivity and allowed to find out about the activation synergy between the wrist and finger flexors and between the wrist and finger extensors.

The research carried out in the second part of this publication made it possible to determine the activity curve, the curve necessary for the numerical description of muscle contraction during the flexion-extension movement in the elbow joint. The results of the research indicate the short head of the biceps muscle as the most active muscle during the flexion movement. This confirms the earlier selection of the flexion movement in the elbow joint as the most isolating and activating movement that activates the short head of the biceps. In addition to the obvious activity of the two heads of the biceps brachii, during the flexion movement, the lateral head of the triceps brachial muscle is also active. The extensor head was constantly active at a significant level. Additionally, there is a noticeable increase in its activity as it approaches maximum flexion in the elbow joint. The cooperation of the triceps muscle of the lateral head of the arm is most likely due to the supporting effect in stabilizing the joint during this movement. In the case of extension in the elbow joint, there is a visible difference between the activity of the triceps and biceps muscles. The agonist muscles are responsible for the performance of the movement and are at a similar level of activity. The values of the agonist activity during extension are lower than the values of the agonist activity during the flexion movement. In the case of the triceps brachii, all three heads work closely together. However, the performed non-invasive tests make it impossible to determine the level of activity of the median head of the triceps muscle of the arm due to its location. EMG measurements without the use of a concentric needle apply only to the study of the bioelectrical activity of muscles using surface electrodes, as was the case here.

The presented series of experimental studies is part of the work aimed at describing and reproducing the work of the muscles of the upper limb of a given patient as accurately as possible. The finite element method will enable us to carry out numerical analyses for active muscles described by the Hill model and to take muscle deformation into account.

5. Conclusions

The series of our articles presents a number of experimental studies conducted in order to determine the parameters for one patient, for whom a personalized numerical model of the upper limb will be ultimately created. Static measurements were carried out to determine the maximum values of the torques. Dynamic measurements allowed for the determination of activity curves during the movement of the upper limb. The works present the method used to determine the desired parameters describing the muscle contraction on the basis of non-invasive experimental studies.

Future work is going to be based on further delineation of parameters describing muscle contraction and development of computer models.

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