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Article

Estimating Surface EMG Activity of Human Upper Arm Muscles Using InterCriteria Analysis

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Abstract: Electromyography (EMG) is a widely used method for estimating muscle activity and could help in understanding how muscles interact with each other and affect human movement control. To detect muscle interactions during elbow flexion and extension, a recently developed InterCriteria Analysis (ICrA) based on the mathematical formalisms of index matrices and intuitionistic fuzzy sets is applied. ICrA has had numerous implementations in different fields, including biomedicine and quality of life; however, this is the first time the approach has been used for establishing muscle interactions. Six human upper arm large surface muscles or parts of muscles responsible for flexion and extension in shoulder and elbow joints were selected. Surface EMG signals were recorded from four one-joint (pars clavicularis and pars spinata of m. deltoideus [DELcla and DELspi, respectively], m. brachialis [BRA], and m. anconeus [ANC]) and two two-joint (m. biceps brachii [BIC] and m. triceps brachii-caput longum [TRI]) muscles. The outcomes from ten healthy subjects performing flexion and extension movements in the sagittal plane at four speeds with and without additional load are implemented in this study. When ICrA was applied to examine the two different movements, the BIC–BRA muscle interaction was distinguished during flexion. On the other hand, when the ten subjects were observed, four interacting muscle pairs, namely DELcla-DELspi, BIC-TRI, BIC-BRA, and TRI-BRA, were detected. The results obtained after the ICrA application confirmed the expectations that the investigated muscles contribute differently to the human upper arm movements when the flexion and extension velocities are changed, or a load is added.

Keywords: electromyography; InterCriteria analysis; muscle interactions; upper arm

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1. Introduction

Daily human movements require strong coordination between the central nervous system (CNS) and muscles, each of which comprises hundreds of motor units. The coordination of multiple motor units to support postural and motor control complicates CNS activity. There is physiological evidence for simple strategies existing to generate a large range of movements, which disburden the CNS [1]. These are synergies, representing muscle interactions, that facilitate motor control and are controlled by motor cortical areas and afferent systems. Tresch and Bizzi [2] observed that simultaneous stimulation of two sites in the spinal cord resulted in a simple linear summation of the responses evoked from each site separately. Mussa-Ivaldi et al. [3] demonstrated that linear combinations of primary field stimuli can generate a wide range of movement patterns and postural control. These results were observed in amphibians, but Tresch and Bizzi [2] suggest that the same may occur in mammals, too. Furthermore, the observed microstimulation responses suggest a modular organization of the spinal cord. The spinal module can generate a motor signal to evoke a specific muscle activation pattern [3,4]. A small set of muscle synergies can explain the complex spatiotemporal patterns of muscle activity [1,5,6]. Most voluntary movements result from the activation of several muscle synergies, provoking a complex electromyographic pattern in the limb muscles.

Electromyography has become a standard method for finding coordination patterns for analyzing muscle synergies and for evaluating motor control strategies [7–10]. Andrea et al. [11] recorded EMG signals of 19 shoulder and arm muscles during point-to-point movement. Then, using an optimized function, they determine four to five muscle synergies using amplitude analysis. When the movement was repeated, but this time with a load and starting from different positions of the forearm, the identified synergies remained highly persistent. Buchanan et al. [12] investigated EMG activity patterns of elbow muscles in fourteen healthy subjects. They recorded the activity of five muscles that act in flexion, extension, pronation, and supination of the forearm. When a movement is performed, along with the expected muscle activation, the authors notice abnormal one appears. The observed muscle activation is not related to the given movement and has no mechanical role in creating the torque. For example, when elbow extension is combined with supination, the m. biceps brachii is highly active, even though its function is related to elbow flexion. According to the authors, this activity probably compensates for the resulting unwanted torque from other muscles, such as the m. biceps brachii and m. pronator teres, even though they induce elbow flexion. Considering muscle activation in unexpected motions, the authors argue that muscle synergies are quite unusual for a human elbow joint, and the relationships between muscle activities depend on the situation.

Jamison and Caldwell [13] also suggested that synergistic elbow muscle connections are dynamically related to the arm task in all applicable degrees of freedom during movement. Examining the EMG signals of the m. brachioradialis, m. triceps brachii, and m. biceps brachii (different parts) for twenty healthy volunteers, the EMG amplitude of the m. biceps brachii responded strongly to torque changes during flexion combined with pronation or supination. This muscle is more active in flexion with supination, but its activity decreases during a combination of flexion with pronation. The m. brachioradialis trend follows a reverse course. These inversely related responses highlight the importance of muscle function understanding in more than one degree of freedom of motion and the importance of various synergistic relationships.

This study is focused on a different strategy for finding muscle synergies, referred to here as muscle interactions. Following the increasing scientific interest in the InterCriteria analysis (ICrA) concept [14], a recently developed approach has been applied to detect muscle interactions in shoulder and elbow joints in healthy subjects. ICrA has been used for real-world task solving in various fields, such as medicine [15–17], computer-aided drug design [18,19], ecology [20,21], artificial intelligence [22–24], e-learning [25], etc. Thus, the idea of testing ICrA to assess the surface EMG activity of upper arm muscles intuitively appears.

The present investigation aims to examine the repeatability and similarity of muscle synergies in healthy subjects during variable conditions (velocity and weight). In this paper, ICrA is applied to establish muscle interactions along the elbow-shoulder kinetic chain, when performing elbow movements in the sagittal plane.

In Section 2 (Methods), the EMG investigation and implemented ICrA method are described. In Section 3 (Results) the obtained results are presented and analyzed. A comparison of the results with relevant searches is given in Section 4 (Discussion). Section 5 (Conclusions) highlights the essence of the work.

2. Methods

2.1. EMG Method

Fifteen healthy volunteers, including men and women over 18 years and under 65 years with no complaints regarding the musculoskeletal and nervous systems, participated in the study. The experimental procedure was approved by the Ethics Committee of the Institute of Biophysics and Biomedical Engineering. Each participant acquainted himself with the experimental protocol and signed an informed consent for participation.

The procedures for electrode placing and performing the motor tasks were strictly followed as they are described in http://www.seniam.org/ [26]. The telemetric system Telemyo 2400G2 of Noraxon, Inc. (Scottsdale, AZ, USA) (8-channel) was used for the study.

The "Skintact-premier" F-301 Ag/AgCl circle electrodes (30 mm diameter) are used for assessing surface EMG signals. Surface electromyography is preferred in muscle coordination examinations because it is not invasive, does not provoke pain, and can be performed easily by nonmedical personnel. The complications of the approach include crosstalk detection; processing methods, such as amplitude normalization; and determination of the start and end of the activity [27]. The sampling frequency was 1500 Hz. The investigated muscles of the right hand were: two pars of m. deltoideus, clavicularis and spinata (DELcla, DELspi); m. biceps brachii (BIC); and m. triceps brachii–caput longum (TRI), m. brachialis (BRA), and m. anconeus (ANC).

The participants were seated on a chair without armrests, and the following motor tasks were performed sequentially:

1. Rest position. Both arms were in a relaxed position beside the body. The participant held that position for one minute.
2. Maximal isometric contractions. The subject was asked to assume several positions of the elbow and shoulder. The examiner applied adequate force to provoke separately the maximum isometric effort of the investigated muscles.
3. Flexion in the sagittal plane. From the rest position, the participant performed some cycles of full-range elbow flexion in the sagittal plane: full flexion; a 5 s rest period in the reaching position; an extension to the initial position; a 5 s rest period in the reaching position. These movement cycles were repeated for a minute. These motions were performed with four different velocities, from very slow to fastest, and these velocities were controlled by a computer tabata program (each change from motion to the held position is regulated by sound and visual markers on the computer's monitor). The time durations for flexion and extension were 10 s (1flex/1ext), 6 s (2flex/2ext), 2 s (3flex/3ext), and 1 s (4flex/4ext) consecutively. The symbols in the parenthesis are the abbreviations used in this paper. The rest at the end position was 5 s.
4. Flexion in the sagittal plane with added weight. A wristband with a weight of 0.5 kg was placed at the wrist, and the same flexion-rest-extension tasks were performed. Periods for flexion and extension were 10 s (1flexW/1extW), 6 s (2flexW/2extW), 2 s (3flexW/3extW), and 1 s (4flexW/4extW). As noted above, the accepted abbreviations are given in parentheses.

Movement 4 repeats movement 3 regarding the speed and arm position but with an added load of 0.5 kg to the wrist of each subject. For clarity, a picture of the experimental setup with the raw EMG signals is presented in Figure 1. The row signals were detected during flexion-rest-extension for 6 s (per active phase) in the sagittal plane with a load of 0.5 kg. The first channel (blue) is for DELcla, the second channel (green) is for DELspi, third channel (red) is for BIC, fourth channel (yellow) is for TRI, fifth channel (purple) is for ANC, sixth channel (dark green) is for BRA, and the seventh and eighth channels are for the 2D goniometer for better orientation for starting and ending the movements. On the right, electrode placement is observed. Sensors are secured with additional yellow kinesiotape for better adhesion and to minimize electrode movement artifacts.

After an initial observation of the EMG recordings, only those taken from four men and six women were analyzed. The other five were excluded because of several reasons, including the presence of abnormal spikes that are not amenable to filtration, inability to follow the required experimental rhythm, failure to keep the exact position of the arm during the entire movement, many cable fluctuations, EMG contamination, and lack of stable recording.

The experimental data for EMGs during the rest positions were first processed. Data were subject to filtration (Butterworth high-pass filter, 4th order, cut-off frequency 20 Hz; Butterworth low-pass filter, 4th order, cut-off frequency 350 Hz) [28]. The same filters were applied over EMGs recorded during maximal isometric contractions, and 6 coefficients for the normalization of the EMGs during movements were calculated. For each movement task, the same filtration was performed, and normalization using the calculated coefficients was performed. Only one trial from each movement cycle for flexion and extension was chosen after careful visual inspection. The start and end of flexion and extension motions were determined, and one time period was chosen. In these intervals, the EMG data were rectified and smoothed (20 samples). The area under the obtained curves was calculated and divided into the respective time intervals. ICrA, briefly presented in the next subsection, is applied to the obtained values.

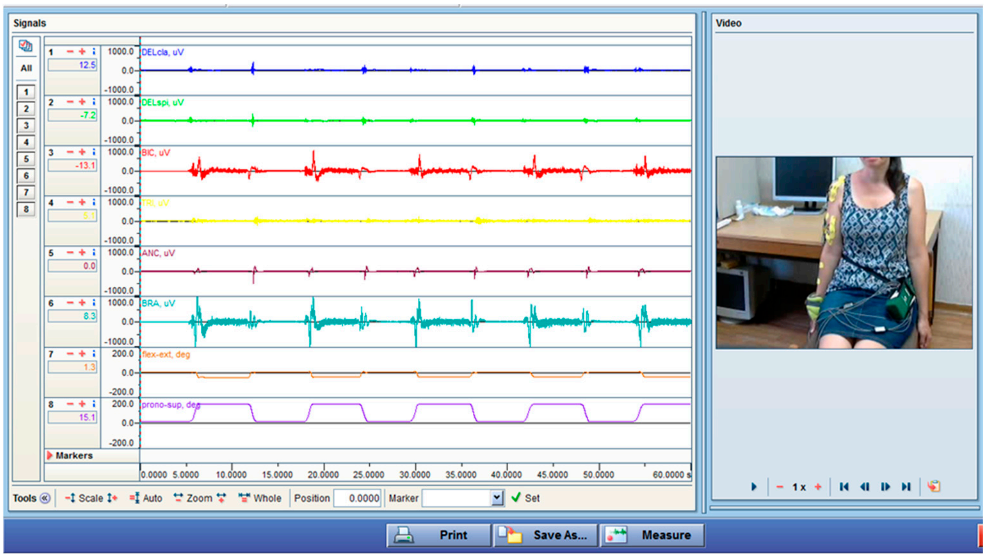

Figure 1. A picture of the experimental setup with raw EMG signals.

2.2. InterCriteria Analysis Approach

InterCriteria analysis based on index matrices (IMs) as tools for structuring the input data and intuitionistic fuzzy sets (IFSs) as tools for considering uncertainty is a recently developed approach to support decision-making in multi-criteria tasks. This method was proposed by Atanasov et al. [14] and enables searching for correlations between criteria by which multiple objects are measured or evaluated. With the aid of ICrA, both existing correlations known from the literature and new ones extracted from the input data can be discovered. Based on the identified correlations, some of the criteria that make measurements more expensive, slower, and resource-intensive could be eliminated and replaced by criteria that make measurements cheaper, faster, and easier without significant loss of accuracy. IFS integration in the ICrA approach supports the more accurate process of decision-making, accounting for uncertainty in the final correlation estimations.

For ICrA application purposes, the input data are structured in an index matrix form that consists of the criteria (for rows) and objects evaluated by observed criteria (for columns):

$$A = \begin{array}{c|ccccccc} & O_1 & \ldots & O_i & \ldots & O_j & \ldots & O_k \\ \hline C_1 & e_{C1,O1} & \ldots & e_{C1,Oi} & \ldots & e_{C1,Oj} & \ldots & e_{C1,Ok} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ C_p & e_{Cp,O1} & \ldots & e_{Cp,Oi} & \ldots & e_{Cp,Oj} & \ldots & e_{Cp,Ok} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ C_q & e_{Cq,O1} & \ldots & e_{Cq,Oi} & \ldots & e_{Cq,Oj} & \ldots & e_{Cq,Ok} \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ C_m & e_{Cm,O1} & \ldots & e_{Cm,Oi} & \ldots & e_{Cm,Oj} & \ldots & e_{Cm,Ok} \end{array}$$

where $C_1 \ldots C_m$—criteria applied to the considered objects; $O_1 \ldots O_k$—objects that were evaluated; $e_{C_1,O_1} \ldots e_{Cm,Ok}$—IM elements (evaluations). Depending on the type of data, IM elements can be real numbers, intuitionistic fuzzy pairs, functions, or predicates.

According to the multi-dimensionality of the input data, the size of the IM varies. In the two-dimensional (standard) case of ICrA, a pairwise comparison between every two different criteria along all evaluated objects is performed based on the relation R. Depending on the type of the relations two counters are generated. The value of the first counter is incremented when both relations are the same (<, < or >, >), while the value of the second counter is incremented when two different relations (<, > or >, <) are detected between two data pairs. Thus, from the initial index matrix A with k objects and m criteria, an index matrix A^* that is $m \times m$ in size is formed. The elements of newly performed IM are intuitionistic fuzzy pairs (IFPs) with values in the interval $[0, 1]$, corresponding to the levels of positive or negative consonance or dissonance between each pair of criteria.

$A^* =$

	C_1	...	C_m
C_1	$\mu_{C1,C1}, \upsilon_{C1,C1}$	...	$\mu_{C1,Cm}, \upsilon_{C1,Cm}$
...	...	...	...
C_m	$\mu_{Cm,C1}, \upsilon_{Cm,C1}$	...	$\mu_{Cm,Cm}, \upsilon_{Cm,Cm}$

The IFP elements, μ and υ, might be interpreted according to different survey purposes as a degree of validity and non-validity, correctness and non-correctness, agreement and disagreement, etc. For most of the obtained pairs the sum $\mu + \upsilon = 1$, but in some cases, there might be pairs for which $\mu + \upsilon < 1$. The difference π is considered as a degree of "uncertainty": $\pi = 1 - \mu - \upsilon$.

If a user's chosen threshold values of α and β for comparison of $\mu_{Cp,\ Cq}$ and $\nu_{Cp,\ Cq}$ are in the interval [0, 1]. Then, the criteria C_p and C_q are in positive consonance. If $\mu_{Cp,\ Cq} > \alpha$ and $\nu_{Cp,\ Cq} < \beta$, the criteria are in negative consonance. If $\mu_{Cp,\ Cq} < \beta$ and $\nu_{Cp,\ Cq} > \alpha$, the criteria are in dissonance.

As a final step of ICrA implementation, the correlation degrees between criteria, namely positive consonance, negative consonance, or dissonance, are determined according to the presented scale in Table 1.

Table 1. ICrA scale for consonance and dissonance according to the μ-values.

Meaning of Consonance and Dissonance According to μ-Values
(0.95, 1.00]—strong positive consonance
(0.85, 0.95]—positive consonance
(0.75, 0.85]—weak positive consonance
(0.67, 0.75]—weak dissonance
(0.57, 0.67]—dissonance
(0.43, 0.57]—strong dissonance
(0.33, 0.43]—dissonance
(0.25, 0.33]—weak dissonance
(0.15, 0.25]—weak negative consonance
(0.05, 0.15]—negative consonance
[0.00, 0.05]—strong negative consonance

The colors in Table 1 correspond to those implemented in ICrAData software [29]. The magenta marked values denote dissonance, and green color is used for positive consonance. The values for negative consonance are given in red.

From a practical point of view, the most informative cases for correlation dependences between observed criteria are those in which positive or negative consonance is observed, in other words when positive or negative consonance is as large or as small as possible. At the same time, the dissonance cases provide less information and can be omitted.

In this paper, ICrA was applied to find muscle interactions when flexion and extension movements in the sagittal plane were performed. The obtained results are analyzed in the next section.

3. Results

Electromyographic data from ten healthy subjects performing flexion and extension at four velocities with and without added weight of 0.5 kg at the wrist were used for the present study. ICrAData software, version 2.5 [29] with a μ-biased selected algorithm for comparison, was applied for data assessment. The software is freely available for users at: http://intercriteria.net/software/.

3.1. Results for Flexion with Different Velocities with and without an Additional Load in the Sagittal Plane after ICrA Application

An initial index matrix for ICrA with the six investigated muscles (DELcla, DELspi, BIC, TRI, ANC, and BRA) as criteria and the ten subjects as objects, were constructed for finding muscle interactions during flexion. The results after the ICrA application are presented in Table 2.

Table 2. Results for flexion movements after ICrA application. The magenta values indicate dissonance, while the green color denotes positive consonance.

Flexion	1flex	2flex	3flex	4flex	1flexW	2flexW	3flexW	4flexW
DELcla-DELspi	0.51	0.49	0.47	0.51	0.67	0.56	0.62	0.53
DELcla-BIC	0.47	0.53	0.53	0.62	0.62	0.56	0.58	0.49
DELcla-TRI	0.56	0.69	0.64	0.73	0.73	0.60	0.64	0.69
DELcla-ANC	0.62	0.73	0.80	0.76	0.49	0.62	0.73	0.76
DELcla-BRA	0.44	0.60	0.49	0.62	0.73	0.56	0.67	0.44
DELspi-BIC	0.51	0.73	0.76	0.62	0.78	0.78	0.73	0.69
DELspi-TRI	0.60	0.67	0.56	0.56	0.67	0.64	0.53	0.62
DELspi-ANC	0.67	0.71	0.62	0.67	0.42	0.62	0.71	0.69
DELspi-BRA	0.49	0.67	0.67	0.67	0.80	0.87	0.69	0.64
BIC-TRI	0.73	0.80	0.67	0.67	0.62	0.69	0.62	0.62
BIC-ANC	0.62	0.62	0.64	0.64	0.51	0.62	0.62	0.56
BIC-BRA	0.84	0.84	0.82	0.73	0.76	0.78	0.73	0.73
TRI-ANC	0.71	0.69	0.62	0.58	0.53	0.53	0.60	0.67
TRI-BRA	0.80	0.82	0.71	0.62	0.73	0.69	0.67	0.53
ANC-BRA	0.60	0.60	0.56	0.60	0.62	0.58	0.58	0.56

All data in Table 2 is rounded to the second digit after the decimal point.

Considering different flexion movements (Table 2), various muscle interactions in weak positive consonance were detected. The only exception is 3flexW, where all muscle couples are in dissonance. ICrA detects the most muscle interactions (three pairs) for 2flex, 3flex, 1flexW, and 2flexW. For the other cases (1flex, 4flex, and 4flexW), less than three interacting muscle pairs were observed. Thus, it can be concluded that the observed muscle interactions depend not only on velocity and added load, but the specific manner of execution of the flexion movements.

The specific case 3flexW is presented in Figure 2 as a detected exception. The left panel of Figure 2 presents the input data, the central panel shows the result after ICrA implementation, and the graphical visualization of the results is given in the right panel.

Additional explanations for Figure 2: The input data are pasted into the left side of the ICrAData window. The μ-biased algorithm is used by default. However, altogether five ICrA algorithms are embedded in the software, and each of them can be selected from the drop-down menu. When the "Analysis" button is chosen, the results are calculated and displayed. The μ and υ values for each pair of criteria are displayed in two matrices (software tables). The default values of thresholds α, β and decimal digits of the obtained results are 0.75, 0.25, and 4 digits, respectively. The outcomes are graphically presented on the right panel as points in the intuitionistic fuzzy triangle.

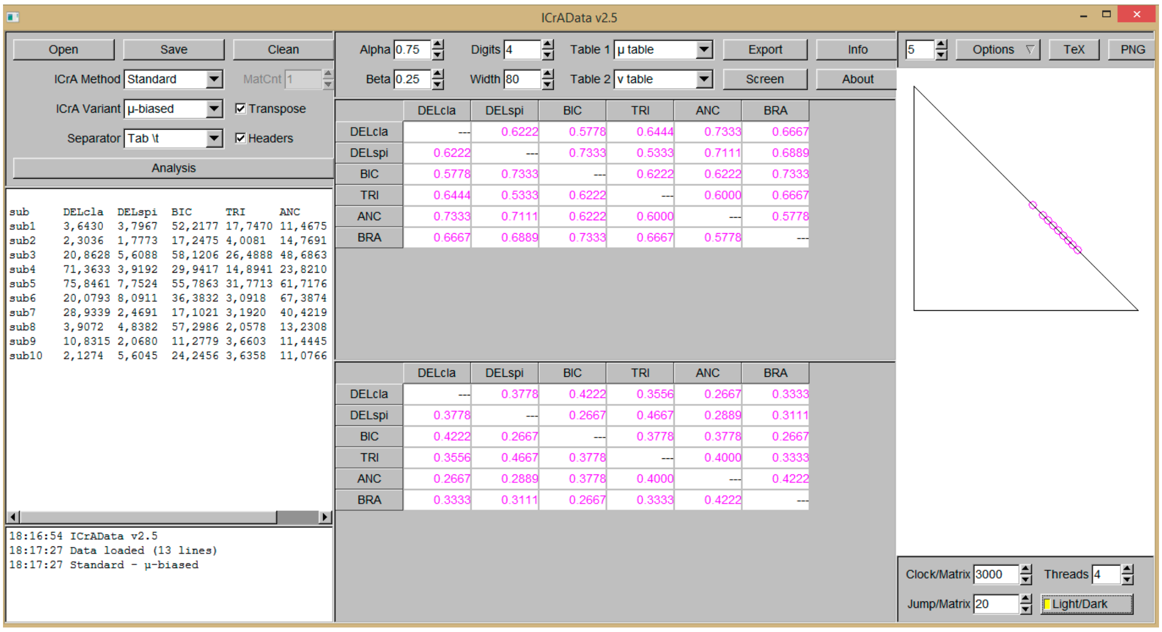

Figure 2. ICrA for the case of 3flexW.

According to the ICrA scale for consonance and dissonance (Table 1), results from Table 2 are summarized in Table 3.

Table 3. Summarized results for flexion after ICrA application.

Consonance/Dissonance	Number of Muscle Pairs in Consonance/Dissonance	Interacting Muscles and the Number of Detected Cases in Consonance
Positive consonance: (0.75, 0.85]—weak positive consonance	16	DELcla-ANC–3; DELspi-BIC–3; DELspi-BRA–2; BIC-TRI–1; BIC-BRA–5; TRI-BRA–2;
Dissonance	104	-
Negative consonance	0	-

Fifteen pairs of muscles and their interactions are the focus of this investigation. According to the results presented in Table 2 during flexion, ICrA detected interactions between six muscle pairs, namely DELcla-ANC, DELspi-BIC, DELspi-BRA, BIC-TRI, BIC-BRA, and TRI-BRA. A weak positive consonance was observed for all of them. ICrA did not find any kind of consonance for nine muscle pairs, including DELcla-DELspi, DELcla-BIC, DELcla-TRI, DELcla-BRA, DELspi-TRI, DELspi-ANC, BIC-ANC, TRI- ANC, and ANC-BRA. Going deeper in detail, as can be seen in Table 3, a total of 16 muscle interactions exhibit positive consonance, while the remaining 104 exhibit dissonance.

Considering movements with different durations (Table 2), it can be observed that for 2flex, 3flex, 1flexW, and 2flexW, ICrA detects three pairs of interacting muscles in positive consonance for each movement. While for 2flex and 3flex movements, interacting muscles are different: BIC-TRI, BIC-BRA, TRI-BRA, and DELcla-ANC, DELspi-BIC, BIC-BRA, respectively, for 1flexW and 2flexW they are the same: DELspi-BIC, DELspi-BRA, and BIC-BRA.

TRI-BRA interaction is found in slow flexion movements (1flex and 2flex). BRA is considered a highly active muscle in slow and fast elbow flexion in prone, semi-prone, and supine positions [30]. At the same time, TRI (the long head) is a reserve during extension and less used in comparison with the other two heads of m. triceps brachii [30]. On the other hand, when the load is added (1flexW and 2flexW), an interaction of one- and two-joint muscles is detected: DELspi-BIC and DELspi-BRA. Arm movements lead to the activation of the three parts of m. deltoideus [30]. In the study by Diplock et al. [31], the authors define BIC as a muscle responsible for shoulder stability. Considering that the exercise is performing the movement in a forward-backward direction in the elbow, the DELspi-BIC couple is supposed to act as stabilizers in the shoulder.

Identical muscle interactions were found between DELcla-ANC when performing flexion with and without weight at the fastest velocity—4flex and 4flexW. A weak positive consonance was observed for DELcla-ANC, while the other 14 muscle interactions remain in dissonance in the abovementioned cases. Here, ICrA detects only one interaction in positive consonance for each movement between two muscles that are not directly involved in performing elbow flexion. The first muscle DELcla assists in the flexion of the shoulder and inward rotation of the humerus. The second muscle, ANC, assists in the extension of the elbow joint and provides stability to the humero-ulnar joint. Since these are fast movements requiring explosive force, with the activation of a large number of fast motor units, it is assumed that torques (inertial, from two-joint muscles) arise in the elbow and shoulder joints, which must be neutralized. According to Papaxantis et al. [32], during upward movements, the values of the gravitational torque exerted around the shoulder joints increase, whereas these values decrease in the elbow joints. The ANC along with some ligaments, elbow extensors, and m. supinator act as dynamic stabilizers of the elbow joint [33]; therefore, it is logical that they are active. Furthermore, when the elbow is flexed beyond 90 degrees, the head of the radius moves slightly distally, suggesting that it must be supported by the ligamentomuscular complex.

In this study, the thresholds that determined intervals for μ-values (Table 1) are set as $\alpha = 0.75$ and $\beta = 0.25$ by default. However, these threshold values may be determined by users according to the type and purpose of the study. If a value of α is set at 0.73 instead of 0.75, the results presented in Table 2 show a sustainable interaction in positive consonance in one muscle pair, namely BIC-BRA. According to Basmajian and Latif [34], both muscles are flexors and act simultaneously in the elbow joint. Also, Naito et al. [35] demonstrate that when the activity of m. brachialis decreases, the activity of m. biceps brachii increases in rapid prono-supination movements at different elbow positions.

3.2. Results for Extension with Different Velocities with and without an Additional Load in Sagittal Plane after ICrA Application

When extension is examined, the initial index matrix for ICrA analysis is performed in the same manner as noted for flexion but considering EMG data from different extension movements for all ten investigated subjects. The results after the ICrA application are presented in Table 4.

Considering extension movements, again as in flexion, different interactions were observed. As can be seen from Table 4, ICrA detects the most muscle interactions in weak positive consonance (four couples) for 3extW, while all muscle couples are in dissonance for 3ext and 1extW. ICrA found two muscle interactions for 1ext and 4extW and only one for 2ext and 2extW. Here, in extension movement, again as in flexion, it can be concluded that the detected interactions depend on the individual specifications and the manner of the movement executions. However, if one compares the results from Tables 2 and 4, it is obvious that ICrA detects less muscle interactions in positive consonance during extension.

For clarity, the specific 3extW case where ICrA detects the most muscle interactions in positive consonance is presented in Figure 3.

Table 4. Results for extension movements after ICrA application. The magenta values indicate dissonance, while the green color denotes positive consonance.

Extension	1ext	2ext	3ext	4ext	1extW	2extW	3extW	4extW
DELcla-DELspi	0.51	0.40	0.36	0.40	0.47	0.58	0.60	0.62
DELcla-BIC	0.47	0.49	0.56	0.60	0.58	0.49	0.56	0.58
DELcla-TRI	0.58	0.67	0.73	0.71	0.71	0.62	0.80	0.69
DELcla-ANC	0.69	0.60	0.53	0.64	0.64	0.62	0.64	0.62
DELcla-BRA	0.69	0.56	0.60	0.64	0.73	0.71	0.78	0.67
DELspi-BIC	0.56	0.69	0.71	0.62	0.67	0.69	0.73	0.78
DELspi-TRI	0.80	0.64	0.53	0.64	0.58	0.64	0.76	0.80
DELspi-ANC	0.73	0.58	0.38	0.62	0.51	0.51	0.51	0.60
DELspi-BRA	0.69	0.67	0.44	0.53	0.64	0.78	0.69	0.69
BIC-TRI	0.71	0.73	0.64	0.76	0.60	0.60	0.67	0.71
BIC-ANC	0.60	0.53	0.44	0.60	0.53	0.51	0.47	0.69
BIC-BRA	0.60	0.67	0.64	0.69	0.71	0.69	0.73	0.69
TRI-ANC	0.71	0.71	0.49	0.53	0.62	0.60	0.58	0.53
TRI-BRA	0.80	0.80	0.60	0.62	0.67	0.60	0.76	0.67
ANC-BRA	0.69	0.60	0.53	0.56	0.60	0.64	0.56	0.64

All data in Table 4 is rounded to the second digit after the decimal point.

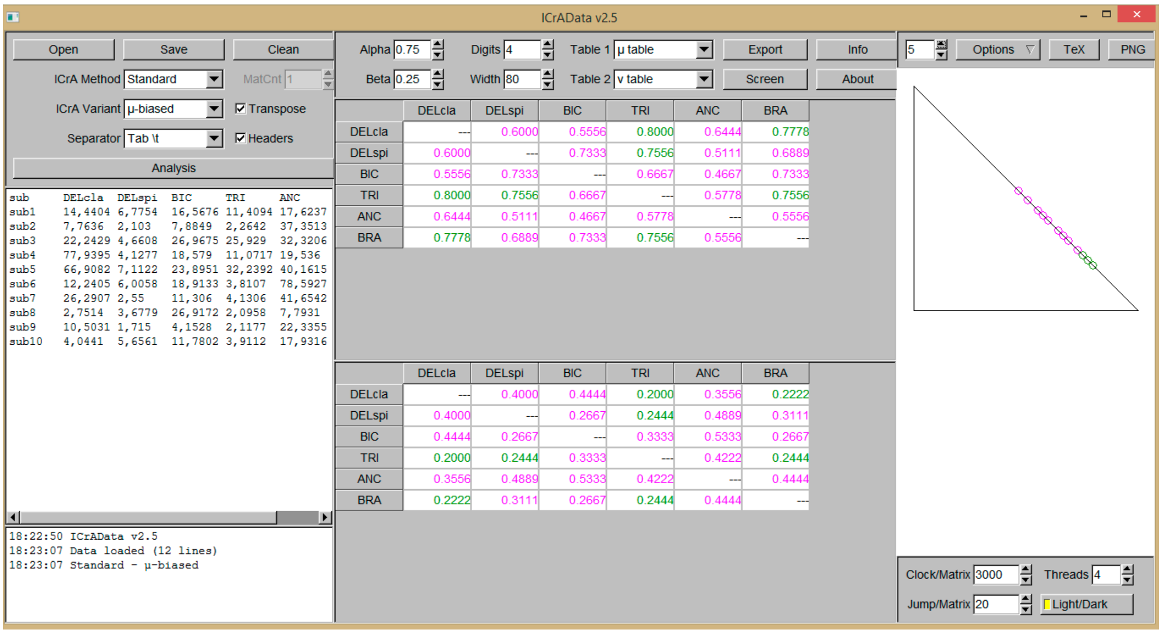

Figure 3. ICrA for the 3extW case.

The results from Table 4 are summarized in Table 5, according to the scale for consonance and dissonance in ICrA (Table 1).

There are two cases with no detected muscle interactions in positive consonance during extension, namely 3ext and 1extW. On the other hand, ICrA detects the most muscle interactions for the 3extW case in which four muscle pairs, namely DELcla-TRI, DELcla-BRA, DELspi-TRI, and TRI-BRA, hit the interval for weak positive consonance. The first three pairs include one shoulder and one elbow muscle. Muscles in the last-mentioned TRI-BRA pair act in the elbow joint and are antagonists, i.e., they have an opposite biomechanical action. Antagonistic muscle activity during slow extension shows variable patterns, but BRA is usually always active [34]. Naito et al. [36] demonstrate that the majority of the elbow flexors are active during the extension phases; however, the patterns and amplitudes of recorded EMG vary between individuals. The extensors (the three heads of m. triceps brachii and m. anconeus) increase their EMG activity during the period of maximum elbow extension, while no EMG activity is recorded in some cases. During elbow movements, except for maximal extension, the TRI was almost inactive, and the long head often showed no EMG activity.

Table 5. Summarized results for extension after ICrA application.

Consonance/Dissonance	Number of Muscle Pairs in Consonance/Dissonance	Interacting Muscles and the Number of Detected Cases in Consonance
Positive consonance: (0.75, 0.85]—weak positive consonance	11	DELcla-TRI–1; DELcla-BRA–1; DELspi-BIC–1; DELspi-TRI–3; DELspi-BRA–1; BIC-TRI–1; TRI-BRA–3;
Dissonance	109	-
Negative consonance	0	-

Again, when extension is considered, all muscle interactions detected after ICrA application are in weak positive consonance, as in flexion. Identical muscle interactions were found after ICrA application for two slow (1ext and 2ext) and two fast extension movements (3extW and 4extW). For the two pairs TRI-BRA and DElspi-TRI, a weak positive consonance was detected.

3.3. Results for Examined Subjects Performing Flexion and Extension Movements after ICrA Application

At the next stage of the investigation, the muscle interactions for each subject during flexion and extension were examined. IMs for all participants were constructed in the following manner: the objects were eight cases of flexion or extension execution and the criteria were the six muscles. The results obtained after the ICrA application are shown in Table 6 and summarized in Table 7.

Table 6. ICrA results for ten subjects when flexion was performed. The magenta values indicate dissonance, green values indicate positive consonance, and red values indicate negative consonance.

Flexion	sub1	sub2	sub3	sub4	sub5	sub6	sub7	sub8	sub9	sub10
DELcla-DELspi	0.93	0.64	0.82	0.89	0.79	0.89	0.68	0.71	0.89	0.79
DELcla-BIC	0.5	0.64	0.75	0.75	0.57	0.89	0.68	0.89	0.68	0.25
DELcla-TRI	0.5	0.61	0.86	0.75	0.57	0.50	0.79	0.82	0.61	0.57
DELcla-ANC	0.32	0.86	0.61	0.79	0.54	0.86	0.82	0.86	0.50	0.68
DELcla-BRA	0.43	0.71	0.87	0.68	0.54	0.93	0.79	0.89	0.64	0.21
DELspi-BIC	0.5	0.64	0.71	0.86	0.58	0.86	0.57	0.75	0.79	0.32
DELspi-TRI	0.5	0.68	0.75	0.86	0.64	0.54	0.68	0.89	0.71	0.64
DELspi-ANC	0.32	0.57	0.5	0.89	0.32	0.96	0.79	0.79	0.61	0.68
DELspi-BRA	0.43	0.57	0.82	0.71	0.61	0.89	0.68	0.82	0.75	0.29
BIC-TRI	0.93	0.96	0.89	1	0.93	0.54	0.89	0.86	0.93	0.61
BIC-ANC	0.82	0.64	0.79	0.89	0.61	0.89	0.5	0.83	0.75	0.29
BIC-BRA	0.93	0.43	0.89	0.86	0.96	0.96	0.89	0.93	0.89	0.96
TRI-ANC	0.82	0.68	0.68	0.89	0.61	0.57	0.61	0.82	0.82	0.68
TRI-BRA	0.93	0.46	0.93	0.86	0.96	0.57	1	0.86	0.96	0.57
ANC-BRA	0.89	0.79	0.68	0.75	0.57	0.93	0.61	0.82	0.86	0.25

All data in Table 6 is rounded to the second digit after the decimal point.

Table 7. Number of detected consonances for flexion.

Flexion	Consonances
DELcla-DELspi	**7/10**
DELcla-BIC	2/10
DELcla-TRI	3/10
DELcla-ANC	5/10
DELcla-BRA	5/10
DELspi-BIC	3/10
DELspi-TRI	2/10
DELspi-ANC	4/10
DELspi-BRA	3/10
BIC-TRI	**8/10**
BIC-ANC	5/10
BIC-BRA	**9/10**
TRI-ANC	4/10
TRI-BRA	**7/10**
ANC-BRA	5/10

As can be seen from Table 6, the muscle interactions are different for each subject. Positive consonance (strong, weak, and only positive) was observed for all detected muscle pairs, except one. DELcla-BRA falls in weak negative consonance when subject 10 was examined using ICrA. Thirteen (the most) muscle interactions were reported for subject 8, while there were only three (the least) for subjects 2 and 10.

If the results of Table 7 are taken into account, four muscle pairs in positive consonance are highlighted for more than half participants. During flexion, the DELcla-DELspi interaction was found in seven of a total of ten subjects. BIC-TRI was detected in eight of ten subjects. BIC-BRA was noted in nine of ten (highest number), and TRI-BRA was observed in seven of ten. The most common interaction found after the ICrA application is BIC-BRA. Anatomically, BRA lies beneath the BIC, and both muscles act simultaneously [34]. They are the main elbow joint flexors, so the correlation found is not surprising. The other marked muscle pairs are between antagonist muscles in the elbow joint, including BIC-TRI and TRI-BRA, and in the shoulder joint, including DELcla-DELspi. During elbow flexion, torques occur in the elbow and shoulder joints, which must be neutralized. For better stabilization of the joint by neuromuscular mechanism, antagonistic co-contraction occurs [37,38].

According to Table 7, four muscle pairs, namely DELcla-ANC, DELcla-BRA, BIC-ANC, and ANC-BRA, can be considered as borderline cases. For five of ten subjects, ICrA detected consonance, while dissonance was found for the other five subjects. Therefore, to obtain more precise results, more subjects should be examined in future work.

The results for the extension movement are presented in Table 8 and summarized in Table 9.

As noted in the results from Table 8, the detected muscle interactions for extension differ for the subjects. Most muscle pairs in consonance are in strong, weak, or only positive consonance. In this case, negative (BIC-TRI and BIC-BRA) and weak negative consonance (DELspi-BIC, DELspi-BRA, and BIC-ANC) were also observed. Here again, ICrA detects less muscle pairs in consonance during extension in comparison with flexion movement.

Considering extension movement, after ICrA application, only one muscle pair, DELcla-DELspi, was detected in positive consonance for more than half participants. During extension, the DELcla-DELspi interaction was detected in six out of ten subjects. Elbow flexion also leads to movement in the shoulder due to the activity of the two-joint muscles, arising moments along the kinetic chain, etc. Shoulder antagonists are activated as a compensatory mechanism for stabilization.

Table 8. ICrA results for ten subjects when extension was performed. The magenta values indicate dissonance, green values note positive consonance, and red values indicate negative consonance.

Extension	sub1	sub2	sub3	sub4	sub5	sub6	sub7	sub8	sub9	sub10
DELcla-DELspi	0.86	0.50	0.89	0.93	0.86	0.79	0.64	0.50	0.82	0.46
DELcla-BIC	0.64	0.25	0.82	0.82	0.57	0.96	0.75	0.54	0.61	0.68
DELcla-TRI	0.68	0.54	0.75	0.68	0.89	0.61	0.50	0.54	0.86	0.61
DELcla-ANC	0.71	0.71	0.68	0.79	0.36	0.79	0.79	0.64	0.75	0.43
DELcla-BRA	0.82	0.75	0.75	0.75	0.64	0.89	0.68	0.61	0.75	0.68
DELspi-BIC	0.57	0.68	0.86	0.75	0.64	0.82	0.46	0.25	0.64	0.21
DELspi-TRI	0.82	0.68	0.71	0.68	0.82	0.61	0.79	0.82	0.75	0.57
DELspi-ANC	0.71	0.36	0.57	0.86	0.29	0.79	0.50	0.71	0.64	0.89
DELspi-BRA	0.82	0.32	0.86	0.68	0.64	0.75	0.89	0.54	0.78	0.21
BIC-TRI	0.39	0.57	0.86	0.71	0.54	0.57	0.25	0.14	0.53	0.36
BIC-ANC	0.36	0.25	0.57	0.68	0.21	0.82	0.68	0.18	0.43	0.25
BIC-BRA	0.68	0.14	0.71	0.86	0.79	0.93	0.57	0.36	0.50	1
TRI-ANC	0.82	0.68	0.57	0.54	0.32	0.75	0.50	0.82	0.89	0.54
TRI-BRA	0.71	0.50	0.64	0.79	0.68	0.57	0.68	0.71	0.89	0.36
ANC-BRA	0.68	0.75	0.50	0.68	0.21	0.82	0.61	0.61	0.86	0.25

All data in Table 8 is rounded to the second digit after the decimal point.

Table 9. The number of detected consonances for an extension.

Extension	Consonances
DELcla-DELspi	**6/10**
DELcla-BIC	3/10
DELcla-TRI	2/10
DELcla-ANC	3/10
DELcla-BRA	2/10
DELspi-BIC	3/10
DELspi-TRI	4/10
DELspi-ANC	3/10
DELspi-BRA	4/10
BIC-TRI	2/10
BIC-ANC	3/10
BIC-BRA	5/10
TRI-ANC	3/10
TRI-BRA	2/10
ANC-BRA	3/10

The BIC-BRA interaction is a borderline case in which the number of consonances is equal to dissonances when the ten subjects are examined. Thus, further investigations are required.

The abovementioned results are discussed in the next section. Also, some ideas for future investigations are outlined.

4. Discussion

The results presented in this paper demonstrate the applicability of ICrA for finding muscle interactions when elbow flexion and extension movements are performed in the sagittal plane.

Some relations between the main results reported here and those already mentioned in the literature are presented in Table 10. As can be seen from Table 10, some antagonistic interrelations of the detected muscle pairs are observed, i.e., the involved muscles have opposite actions. It is supposed that antagonist co-contraction appears as a result of existing neuromuscular mechanisms acting to increase joint stiffness for better stabilization and kinetic control [37,38]. The other detected muscle pairs are agonistic (synergetic), i.e., the muscles work together to create a movement. One of them is a prime mover, and the others have supplementary functions in the full range or just in part of it [39].

Table 10. Main muscle interactions identified using ICrA.

Movement	Antagonistic Muscle Interaction	Agonistic Muscle Interaction	Muscle Pair Function in the Sagittal Plane
Flexion, extension	DELcla-DELspi (one-joint muscles) Acts together in the shoulder joint		The three parts of the m. deltoideus are active in all movements of the arm [30,37,38]. They are considered to be dynamic stabilizers along with rotary cuff muscles and the long head of the m. biceps brachii [40]. Anterior fibers of m. deltoideus have an assistive function in drawing the arms forwards, and posterior fibers act with m. latissimus dorsi and m. teres major in drawing the arm into extension [39].
Flexion	BIC-TRI (two-joint muscles) Acts together in the shoulder and elbow joint		These two muscles are two-joint muscles and act in both the elbow and shoulder joints but in different directions. The BIC is involved in anterior stability of the elbow in the sagittal plane. The posterior stability is enhanced by the m. triceps brachii tendon [31,39]. In the shoulder, the long head of m. triceps brachii keeps the humeral head in the glenoid cavity. It assists in the extension of the shoulder joint. The BIC weakly assists the arm movements at the glenohumeral joint in forward flexion.
Flexion		BIC-BRA (two-joint muscle and one-joint muscle) Acts together in the elbow joint	BIC and BRA are flexors in the elbow joints. BIC is a flexor in a neutral position in the presence of added weight, and BRA is active during flexion in all positions of the forearm [34]. Again, according to these authors, both muscles act simultaneously and are most active in weight-bearing flexion in the neutral position of the forearm. In addition to this statement, Naito et al. [35] demonstrate a clear decrease in m. brachialis and m. brachioradialis activity together with an increase in m. biceps brachii activity during rapid prono-supination movements at the elbow from different positions. However, the authors outline the existence of ingenious reciprocal connections between the elbow flexors, which also confirms the sustained interaction shown as a result here between BIC and BRA.
Flexion	TRI-BRA (two-joint muscle and one-joint muscle) Acts together in the elbow joint		The BRA is highly active in flexion in all forearm positions [30]. The long head of the triceps is the least active in the extension direction compared to the other two heads [36]. The m. brachialis is involved in anterior elbow stabilization in the sagittal plane, the triceps tendon supports the posterior [39].

All mentioned upper limb muscle interactions can be useful for various purposes, namely motor control studies, rehabilitation, industrial applications, sports, synergies examination, etc.

Along with the data described in this article, EMG signals were recorded from the already reported muscles during elbow flexion and extension in the horizontal plane. Due to the changed starting position of the upper arm, it is expected that after the application of the ICrA method, different muscle interactions could be found, with a prevalence of shoulder muscle pair interactions. A classical correlation analysis should be applied for validation of the obtained results.

Also, ICrA as a decision-making method can be used to optimize the experimental protocols. After identifying similarities in muscle performance during the execution of some motor tasks, it is relevant to drop a task to avoid muscle and psychological fatigue, especially if the movements are studied in patients rather than healthy subjects.

5. Conclusions

In the present study, ICrA is used for the first time to assess experimentally obtained EMG data from ten healthy subjects performing elbow flexion and extension in the sagittal plane. After the application of the approach, some pairs of interacting human upper arm muscles are detected.

When the two movements with different durations with and without added weight are observed, the results clearly show one stable interaction in weak positive consonance between BIC and BRA for flexion. However, for extension, no steady interacting muscle couples are observed using ICrA.

On the other hand, when ten different subjects are the focus of the study, ICrA detects four interactions in positive consonance for muscle pairs DELcla-DELspi, BIC-TRI, BIC-BRA, and TRI-BRA for flexion and one interaction in positive consonance for the muscle pair DELcla-DELspi for extension.

Based on the obtained results, it can be concluded that different muscle interactions were detected for flexion and extension movement as well as for each examined subject after ICrA application. Furthermore, it was observed that investigated muscles contribute differently to the control of movements when the movement velocity is changed, or weight is added.

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