

Upper Limb Load as a Function of Repetitive Task Parameters: Part 2—An Experimental Study

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The aim of the study was to compare the theoretical indicator of upper limb load with the physiological indicator of musculoskeletal load, which is present while performing a repetitive task (a normalized electromyography [EMG] amplitude recorded from the muscles of the upper limb involved in the performed task). In an experimental study of a repetitive task, the EMG signal from 5 main muscles of the shoulder girdle, arm and forearm was registered: extensor carpi radialis longus, flexor carpi ulnaris, deltoideus anterior, biceps brachii caput breve and trapezius descendens.

The results of the study showed a strong correlation between the theoretical indicator (Integrated Cycle Load) and the physiological indicator (root mean square of a normalized EMG amplitude from the 5 muscles). This proves that the developed theoretical indicator can be accepted as an indicator of upper limb musculoskeletal load during a work task.

electromyography upper limb handgrip force cycle load

1. INTRODUCTION

It is important to study the relation between the external load imposed by the work environment and the internal load on muscles. Various indicators of musculoskeletal load which results from a performed task were considered in experimental studies. The most frequent were electromyography (EMG) parameters [1, 2, 3, 4, 5, 6, 7], but also heart rate [3, 6], blood pressure [2, 4] and subjective measures [6, 8, 9]. EMG is a good tool for the assessment of internal muscle load. Several studies proved that the force of a muscle is proportional to an EMG amplitude [10, 11, 12, 13, 14]. All those indicators of musculoskeletal load relate to given work conditions described by repetitive task parameters and they can evaluate musculoskeletal load for those conditions only. This means that each

work condition must be assessed experimentally, which makes assessment time consuming and expensive. There is a need for an indicator of load which would be based on the parameters describing the performed task. Such an indicator would make it possible to assess musculoskeletal load on the basis of the values of task parameters without the necessity to conduct an experiment. Thus it would be very useful in designing workplaces.

A theoretical indicator of upper limb musculoskeletal load based on repetitive task parameters was developed in a study presented in Part 1 [15]. It is hypothesized that the indicator based on task parameters correlates with a physiological indicator of musculoskeletal load, a normalized EMG amplitude recorded from the muscles of the upper limb involved in performing the task.

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To prove this hypothesis, an experimental study of repetitive tasks was performed. In that study different variants were characterized by different values of repetitive task parameters. The study was performed for variants of load for which the theoretical indicator of musculoskeletal load (Integrated Cycle Load, *ICL*)—expressing upper limb load—had been calculated. Upper limb load was also assessed on the basis of the physiological indicator of musculoskeletal load based on EMG measurements of the five main upper limb muscles. Verification of the established theoretical indicator of upper limb musculoskeletal load (*ICL*) was performed by comparing theoretical results (*ICL*) and experimental ones (root mean square of a normalized EMG amplitude for the registered five muscles).

2. METHODOLOGY

2.1. Participants

Nine young men, right-hand dominant, aged from 20 to 24 years (average age 21.9 years), were recruited from a group of male students of the Academy of Physical Education in Warsaw, Poland. The participants were healthy, had no history of muscle pain and had similar anthropometric dimensions: their average body mass was 88 kg (from 80 to 93), body height 179 cm (from 177 to 182) (Table 1).

The study was carried out with the approval of the Academy of Physical Education Ethics Committee. Before the experiments, an informed

TABLE 1. Characteristics of Participants

Participant	Age (years)	Body Height (cm)	Body Mass (kg)
MC	20	179	77
MG	22	179	82
MJ	21	178	82
ML	22	177	80
MM	22	179	81
PG	23	178	67
RH	24	182	93
RL	23	181	78
TB	20	178	88
<i>M</i>	21.89	179	80

consent was obtained. The participants were financially compensated for their participation.

2.2. Experimental Layout

Experiments were performed in 12 variants of external load. During the main experiment, a participant performed a repetitive task in an appropriate variant described by the level of the relative force and duration of each of the four periods of the cycle.

Two types of upper limb strength activities were included. They were handgrip force and the force of supporting the upper limb in a determined posture. The duration and external load in each variant of load was presented in detail in Part 1 [15].

Handgrip force and the EMG signal from five muscles were registered during the experiments. Participants performed the task in a sitting position, with their back straight and the left upper limb relaxed (Figure 1).

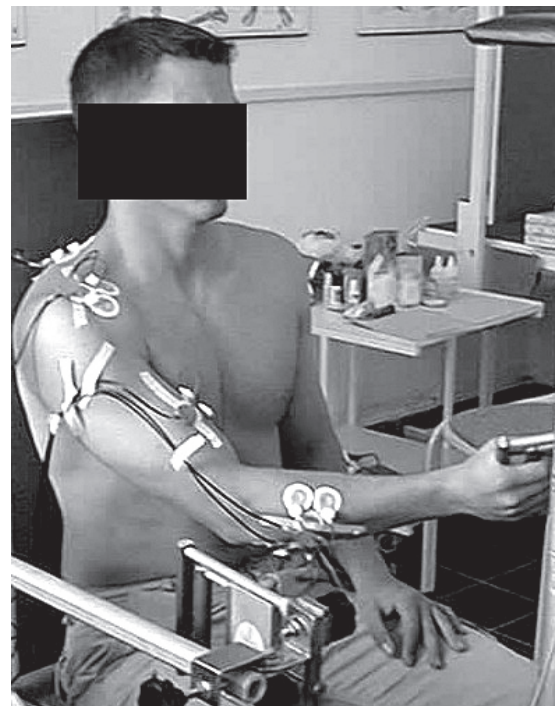


Figure 1. The experimental setup for Boundary Upper Limb Postures A and B.

The sequence of variants was randomized for each participant. During the experiments handgrip force exertion in period 1 and period 3 was imposed by a 5-s sound signal. Keeping the

force level demanded sight control of the force. It was accomplished by presenting the value of the force on a screen. The participant's task was to keep handgrip force at a set level.

2.3. Force Measurements

Handgrip force was measured with a hand dynamometer against which the participants exerted contractions of muscles in static (isometric) tests. The dynamometer was fastened onto a metal support in a position which imposed on the participants exerting handgrip force in a defined upper limb posture. During the test the participants controlled the level of force with a digital meter.

Measurements of grip strength were performed using equipment which consisted of a DR-3 hand dynamometer with a regulated grip span connected through a WT8-RS 8-channel amplifier with a 12-bit analogue-digital converter to a PC-class computer. The equipment was produced by JBA, Poland. The nominal measurement range of the hand dynamometer was 1,200 N with the maximal linear error lower than 5%. The specially developed CPS_v_2.0 software supplied additionally made it possible to register and graphically present the actual value of strength from the dynamometer. After the test it was possible to see the measured value.

2.4. EMG Measurements

2.4.1. Procedure and equipment

The involvement of upper limb muscles in force exertion varies depending on the type of force that is exerted. Activities like lifting, pushing, pulling, pronation and supination—or activities in which force is exerted by the muscles of the hand and forearm only—involve muscles of the whole upper limb. In the experiments, handgrip force was exerted (mostly muscles of the forearm were involved) as well as the force of supporting the upper limb in a determined posture (involving the activity of arm and shoulder muscles).

The following muscles were examined: two muscles of the forearm (extensor carpi radialis

longus and flexor carpi ulnaris), two muscles of the arm (deltoideus anterior and biceps brachii caput breve) and one muscle of the shoulder girdle (trapezius descendens).

Those muscles were selected because they represent the component forces exerted during the experiment, i.e., handgrip force and the weight of the upper limb reflected by the lifting force. Those muscles are comparably big and located just under the skin making surface EMG measurement relatively convenient. The anatomical localization of the muscles was done by feel as participants put them to isometric tension.

A Muscle Tester MESPEC 4000 (Mega Electronics, Finland) and an IBM computer were used to measure and store data. The EMG signal was registered through MS-OOS (Medicotes, Denmark) surface electrodes. To ensure consistent electrode placement for each of the test sessions, the participant's skin was marked around the electrodes. The skin was properly prepared to obtain skin resistance below 2 k Ω . Preamplifiers mounted to the electrodes made it possible to register the non-artefacted signal. The EMG signal was sampled through a 12-bit A/D converter with a sampling rate of 1000 Hz.

2.4.2. Measurements of maximum voluntary contraction of the examined muscles

Before the experiment, tests for maximum tension for each of the examined muscles were performed. For each of the analyzed muscles maximum force occurs in different activities and directions of the exerted force [16, 17]. Therefore four different tests were performed; for forearm muscles—extensor carpi radialis and flexor carpi ulnaris—tests of maximum muscle tension were the same (maximum handgrip force).

During the tests the participants were asked to build up the force gradually without jerking and to hold the exertion for 3 s. Verbal encouragements were offered during the test. The aim of those measurements was to obtain a maximum amplitude of the EMG signal for normalization for each of the analyzed muscles.

Test 1—maximum tension in muscle trapezius pars descendens. A calibration platform equipped with two adjustable slings was

used to measure the maximum EMG signal from trapezius pars descendens. The participant stood on a platform in a neutral position with both arms hanging down. He pulled sling handles. In that body position, values of all seven angles defining the upper limb posture were equal to 0° . The procedure had to be performed by pulling the handle smoothly and by using the shoulders (without flexion in the elbow joint).

Test 2—maximum tension in muscle deltoideus anterior. The same platform was used to exert maximum force for muscle deltoideus pars anterior. The participant was in a sitting position, arms abducted at 45° , flexed in the elbow at 90° . Slings were fastened to the elbow. That upper limb location was defined according to the LIMB model [15] as follows: $q_1 = 45^\circ$; $q_2 = 0^\circ$; $q_3 = 0^\circ$; $q_4 = 90^\circ$; $q_5 = 0^\circ$; $q_6 = 0^\circ$; $q_7 = 0^\circ$. The participant exerted the force by lifting his arms vertically.

Test 3—maximum tension in muscle biceps brachii. Maximum activity of muscle biceps brachii was registered during maximum pulling in the upper limb flexed in the arm at 90° and flexed in the elbow at 90° . The upper limb location was defined according to the LIMB model as follows: $q_1 = 0^\circ$; $q_2 = 90^\circ$; $q_3 = 0^\circ$; $q_4 = 90^\circ$; $q_5 = 0^\circ$; $q_6 = 0^\circ$; $q_7 = 0^\circ$.

Test 4—maximum tension in muscles extensor carpi radialis and flexor carpi ulnaris.

The maximum signal for extensor carpi radialis and flexor carpi ulnaris muscles was accepted as that measured during maximum handgrip force. When exerting force, the participant was in a sitting position with his back straight and left limb relaxed. Respective EMG signals from the muscles were measured for each of the four examined upper limb postures (A, B, C and D). The maximum force measured during this test was used as a reference value for the relative force of the handgrip in the same upper limb posture.

3. ANALYSIS

The EMG signal amplitude registered from upper limb muscles can be an indicator of the differences in musculoskeletal load according to variants of experiments characterized by external load. An example of a raw EMG signal registered during the experiment is presented in Figure 2.

The average EMG amplitude was calculated by full wave rectification followed by integration over 100 ms. The mean value of the average amplitude was calculated over three cycles of the performed

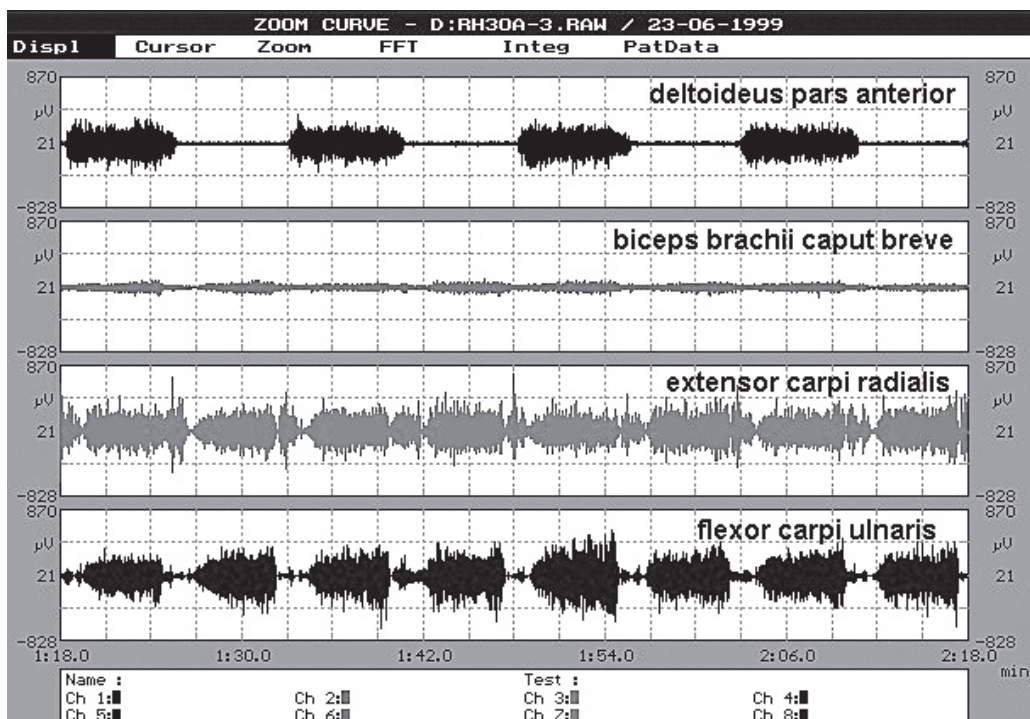


Figure 2. An example of a raw electromyography (EMG) signal registered during the experiment.

task and normalized. The normalization was performed for each muscle according to values of the amplitude measured during maximum force exertion in a test performed separately for each of the examined muscle before the experiments. Normalization was performed according to a procedure described in Mirka [18]. The parameter calculated in this way (NEMG) was considered to be an indicator of muscle tension in a given variant of the experiment.

Differences in a normalized EMG amplitude (NEMG) according to variants of the experiment—which were differentiated according to parameters describing the experiment conditions (the level of the relative force of the handgrip and relative force of supporting upper limb posture)—were examined.

An analysis of the EMG signal was conducted by using software that was part of the ME4000 apparatus. For statistical analysis, Statistica software v. 6 (from StatSoft) was used. To establish differences between specific groups of variants the *t* test was employed.

4. RESULTS

4.1. Musculoskeletal Load Expressed by EMG

Variants of the experiments were differentiated by two factors: the four Boundary Upper Limb Postures, which influenced the force of supporting

the upper limb in the determined posture or upper limb movement, and the level of relative handgrip force exerted in the Boundary Upper Limb Postures. In other words it was differentiated by the level of the force of supporting the upper limb in a determined posture and by the level of handgrip force.

Figure 3 presents values of a normalized amplitude of the EMG signal (NEMG) for muscle trapezius pars descendens registered in each variant of the experiments. The EMG signal was normalized according to the EMG signal registered while performing Test 1. The values of a normalized amplitude for the same Boundary Upper Limb Postures are very similar. There are no differences in to the level of handgrip force.

Figure 4 presents the EMG signal of the deltoideus pars anterior muscle normalized according to the maximum tension as exerted in Test 2. The deltoideus anterior muscle is responsible for supporting the upper limb posture, which is well characterized by the NEMG parameter calculated for variants of the experiments. The influence of the upper limb posture on the activity of deltoideus pars anterior is described by the fact that there are differences in a normalized amplitude value in relation to Boundary Upper Limb Postures but there are no differences according to the level of relative handgrip force.

Figure 5 presents values of NEMG for the biceps brachii muscle. Normalization has been performed according to the EMG signal derived

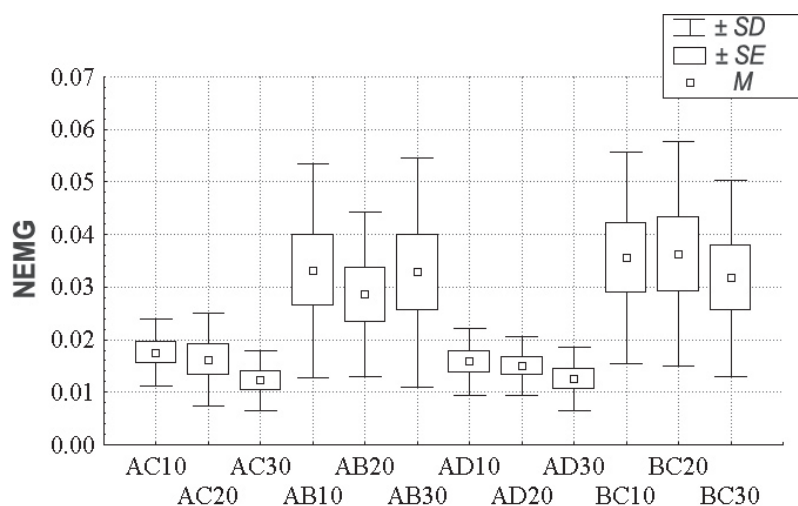


Figure 3. Values of a normalized electromyography amplitude (NEMG) in muscle trapezius descendens according to variants of the experiments (the letters correspond to Boundary Upper Limb Postures).

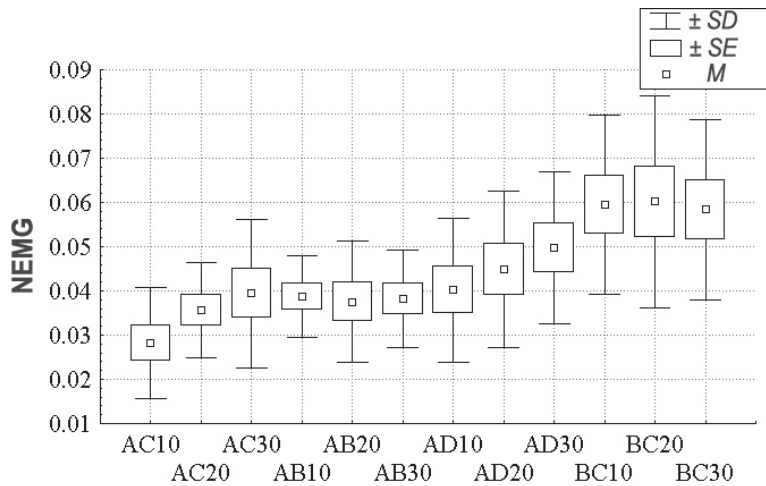


Figure 4. Values of a normalized electromyography amplitude (NEMG) in muscle deltoideus anterior according to variants of the experiments (the letters correspond to Boundary Upper Limb Postures).

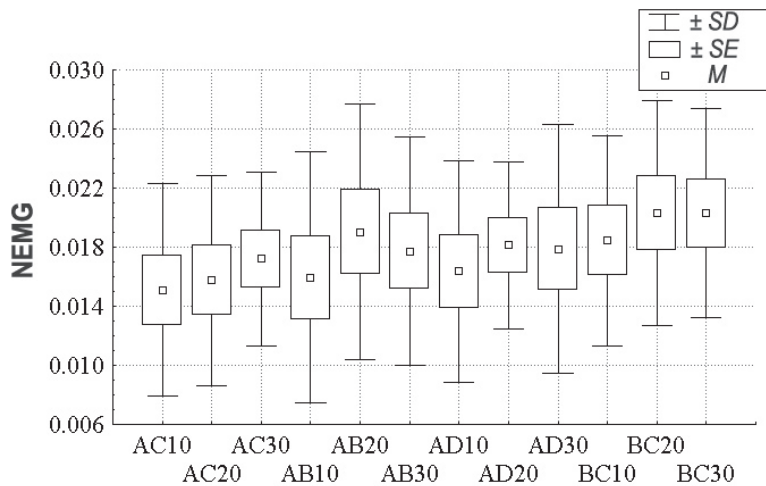


Figure 5. Values of a normalized electromyography amplitude (NEMG) in muscle biceps brachii according to variants of the experiments (the letters correspond to Boundary Upper Limb Postures).

during maximum tension of the muscle in the exertion force in Test 3. Values of the NEMG parameter are on a very similar low level (about 0.02) for all variants of the experiment. There are no differences either according to handgrip force level or to force of supporting the upper limb in the Boundary Upper Limb Postures.

The amplitude of the EMG signal of the extensor carpi radialis and flexor carpi ulnaris muscles normalized to the signal obtained in Test 4 are presented in Figures 6 and 7 respectively. Both of the forearm muscles show similar tendencies in tension. It does not change according to the force of sustaining the upper limb in the determined posture. However, it differs very strongly according to the level of the relative handgrip force.

For each of the examined muscles a *t* test for a group of variants comprising variants with the same Boundary Upper Limb Postures and different relative force levels was performed. It analyzed the differences in a normalized amplitude according to Boundary Upper Limb Postures. There were statistically significant differences only for muscles trapezius pars descendens and deltoideus pars anterior. For muscle trapezius there were statistically significant differences between the following group of variants: AC-AB, AC-AD, AD-AB, BC-AB, BC-AD (the letters correspond to the Boundary Upper Limb Postures). For the deltoideus pars anterior muscle there were statistically significant differences between all the groups of variants comprising variants with the three levels of results for AC and AD.

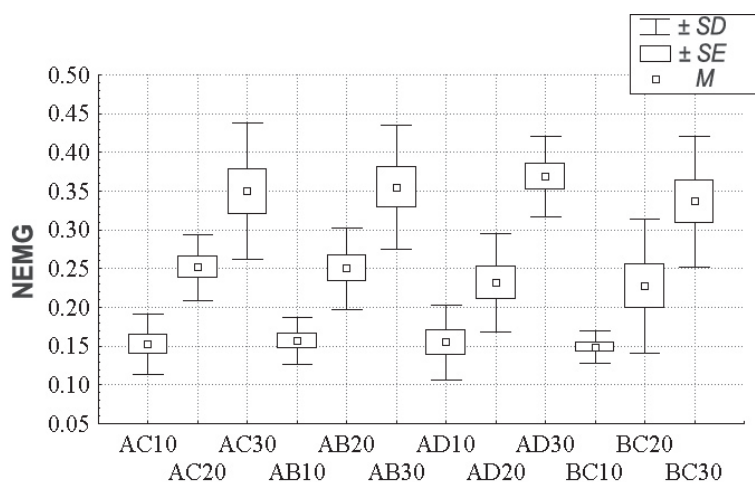


Figure 6. Values of a normalized electromyography amplitude (NEMG) in muscle extensor carpi radialis according to variants of the experiments (the letters correspond to Boundary Upper Limb Postures).

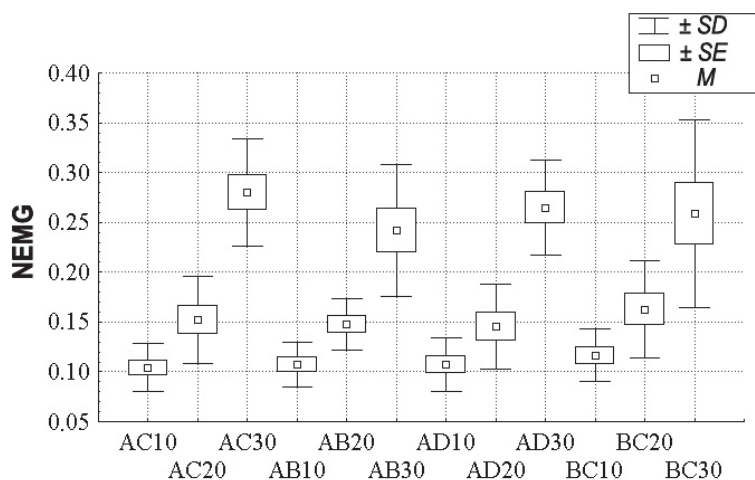


Figure 7. Values of a normalized electromyography amplitude (NEMG) in muscle flexor carpi ulnaris according to variants of the experiments (the letters correspond to Boundary Upper Limb Postures).

For comparison, calculations were done on the physiological indicator of musculoskeletal load. This indicator takes into account a normalized EMG amplitude of the shoulder, arm and forearm muscles. It is expressed as root mean square of a normalized amplitude (NEMG) of the five analyzed muscles. Such an indicator was calculated for each of the participants and each variant of external load. Mean values and standard deviation of the physiological indicator for each variant of the experiment are presented in Table 2.

4.2. The Relationship Between ICL and Physiological Indicator of Musculoskeletal Load

Figure 8 presents values of the theoretical indicator of upper limb external load (ICL) and

TABLE 2. Mean Value and Standard Deviation of Root Mean Square of the Five Examined Muscles of Normalized Electromyography Amplitude (NEMG)

Variant	M	SD
AC10	0.090	0.0253
AC20	0.135	0.0170
AC30	0.205	0.0271
AB10	0.095	0.0155
AB20	0.132	0.0213
AB30	0.195	0.0379
AD10	0.089	0.0191
AD20	0.128	0.0256
AD30	0.206	0.0203
BC10	0.085	0.0201
BC20	0.132	0.0334
BC30	0.195	0.0436

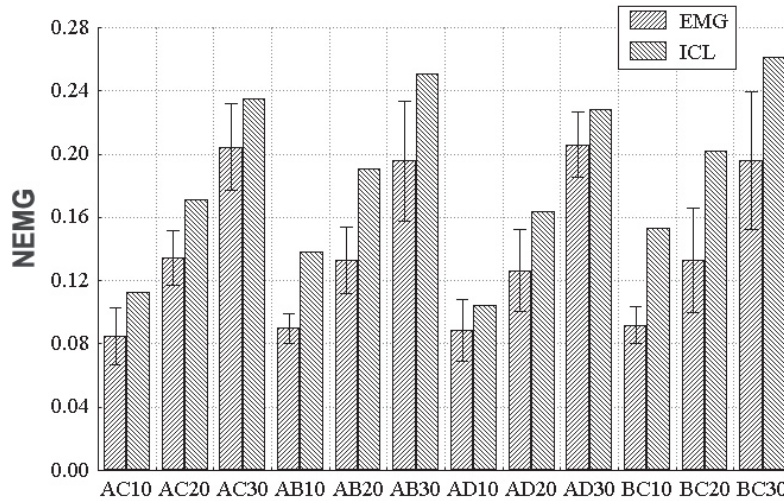


Figure 8. Mean values and standard deviation of the Integrated Cycle Load (ICL) and root mean square of the five examined muscles of a normalized electromyography amplitude (NEMG). Notes. EMG—electromyography.

the physiological indicator of musculoskeletal load of the upper limb assessed on the basis of EMG measurements for each of the variants of the experiment.

In the presented values for both parameters, similar tendencies according to the variants of the experiment are visible. There is strong correlation between values of those two indicators. The relationship between the theoretical indicator (ICL) and the physiological indicator (EMG) of upper musculoskeletal load is presented on Figure 9.

5. DISCUSSION AND CONCLUSION

The results of this study showed that while performing the experimental task, the forearm and hand muscles are mostly activated by handgrip force exertion as the arm and shoulder muscles are by the force of sustaining the weight of the upper limb, which changes according to upper limb posture. An analysis of a normalized EMG amplitude (NEMG) showed that the trapezius descendens and deltoideus anterior muscles were sensitive to changes in upper limb posture.

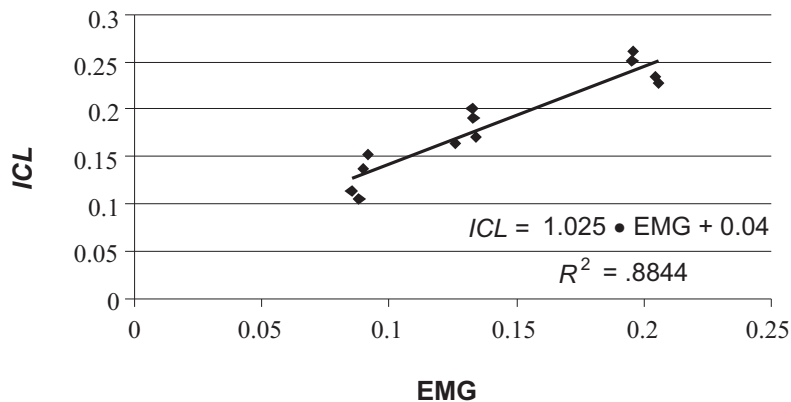


Figure 9. The relationship between the theoretical (Integrated Cycle Load, ICL) and physiological (root mean square of a normalized electromyography amplitude of the five examined muscles) indicator of musculoskeletal load. Notes. EMG—electromyography.

Although the muscles of the forearm extensor, carpi radialis and flexor carpi ulnaris are not sensitive to upper limb posture, they are strongly influenced by the level of relative handgrip force. The obtained results are in step with the results of other studies, which confirmed that an amplitude of the EMG signal registered from the arm and shoulder muscles during a performed study can be a physiological indicator of musculoskeletal load [1, 2, 3, 4, 13, 19].

The extensor carpi radialis longus and flexor carpi ulnaris muscles are responsible for handgrip force exertion. Ohtsuki's [20] study showed correlation between handgrip force and the integrated amplitude of the EMG signal for finger flexor muscles. In the present study apart from those two forearm muscles, the trapezius and deltoideus muscles were also examined. The activities of those two muscles are mostly connected with supporting the weight of the upper limb and tension in those muscles changes according to the upper limb posture [21]. It is generally accepted that the role of the trapezius muscle is to support posture and that this muscle is responsible for upper limb posture [3, 22, 23, 24]. A similar role of the anterior deltoideus and middle deltoideus muscle has been found in the study of Giroux and Lamontagne [25] and Kronberg et al., [26].

ICL expresses upper limb musculoskeletal load as a function of external parameters characterizing the performed repetitive task. The results of the study showed strong correlation between the theoretical indicator (*ICL*) and the physiological indicator (EMG). Although the values differ, what is meaningful is that there is correlation between those two indicators. Both of the indicators have no units (they are dimensionless). The values of the physiological indicator are lower than of *ICL*, which can be due to the fact that a limited number of muscles was taken into consideration.

Taking into consideration the fact that electromyography is a well established and universally approved measure of muscle tension, it can be accepted that the physiological indicator—root mean square of a normalized amplitude of the examined muscle—expresses

muscular load. The strong correlation between *ICL* and the physiological indicator of upper limb load proves that the developed indicator (*ICL*) can be a theoretical indicator of upper limb musculoskeletal load.

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