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Experimental Verification of the Computerized Method for Work Space Optimization in Conditions of Static Work

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The aim of this study was to verify a theoretical model for upper extremity work space optimization. In order to do that, experimental studies were conducted in which two parameters of the electromyography (EMG) signal were analyzed: AMP (amplitude calculated as Root Mean Square) and SZC (coefficient of the slope of the regression line between time and Zero Crossing values). Values of forces in muscles (parameter MOD) were calculated from theoretical studies. A comparison of experimental (AMP, SZC) and theoretical (MOD) parameters was performed by analyzing the coefficient of correlation between those parameters and differentiation of muscular load according to external load value. Analysis showed that the theoretical and experimental results are in step, which means that the developed model can be used for upper extremity work space optimization.

EMG upper extremity load intermittent load constant load

1. INTRODUCTION

Protection against the negative influence of static work can be found in the optimization of work space, that is, choosing from the work space a subspace that requires the least effort from the worker. Using experimental methods for optimization is time-consuming. There are

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studies aimed at finding modern computer simulation methods for the optimization process. Such a theoretical method for upper limb work space optimization has been worked out on the basis of an upper extremity bone-and-muscles model. Two merit criteria that enable optimization of an upper limb work space defined by given parameters were used. The aim of this study was to verify the theoretical method by experiments. Electromyography (EMG) was chosen as the experimental method. During the last few years, EMG has been commonly used for assessing musculoskeletal load. Relations between the amplitude of the EMG signal and muscle force were shown (Basmajian & DeLuca, 1985; Lawrence & DeLuca, 1983). Muscle tension and fatigue can be assessed by EMG signal parameters. EMG is sensitive to all disturbances and inaccuracies also connected with the normalization process of the the EMG amplitude. To minimize those inaccuracies, in those studies two EMG parameters were analyzed and compared with theoretical calculations. Those parameters were obtained from EMG measurements from eight chosen muscles.

2. METHODOLOGY

2.1. Methods

The EMG parameters that can be taken as correlated with those calculated by the computer program force in muscle are muscle tension expressed by amplitude value (AMP) and muscle fatigue assessed as the slope of the regression line of zero crossing (SZC; Hägg, 1981; Hägg, Suurküla, & Liew, 1987; Suurküla & Hägg, 1987).

AMP informs about muscle tension for a given variant of the experiment. EMG signal amplitude analysis requires normalization (Jörgensen, Fallentin, Krogh-Lund, & Jensen, 1988). It is rather difficult to obtain a very precise value of maximum muscle force for a given limb location (every measurement gives a slightly different value). Such a situation can cause additional error in the normalization process (Mirka, 1991). Therefore, although AMP is closer to the calculations of the force in muscles from the computer program parameter (MOD), SZC can also be used in the comparison process.

To find a relation between the experimental and theoretical results, similarities between AMP, SZC, and the values of muscle forces calculated by the computer model (MOD) were analyzed. This analysis was also to find if the theoretical and experimental results are to the same degree sensitive to changes of the external force.

A comparison of the results was conducted on the basis of the measurements from eight muscles:

- flexor carpi radialis (FCR),
- flexor carpi ulnaris (FCU),
- extensor carpi ulnaris (ECU),
- brachioradialis (BR),
- biceps brachii caput breve (BBCB),
- deltoideus (DL),
- triceps brachii caput laterale (TBCL),
- trapezius (TR).

Those muscles were selected because they are quite big and located just under skin so the EMG measurement is relatively easy. Muscle trapezius was not taken into account in the computer model. However, this muscle supports the scapula and many researchers suggest that the upper limb location influences the muscular load of this muscle. That is the reason why in those studies, like in many other ergonomic studies (Christensen, 1986a; Lannersten & Harms-Ringdahl, 1990), this muscle is taken as an indicator of the entire upper limb load. It was hypothesized that EMG parameters for muscle trapezius can be compared with the sum of upper limb muscle forces, which was justified by the fact that the load in this muscle is considered to be an indicator of the load in the whole upper extremity.

2.2. Equipment

Measurement and analysis of the EMG signal were computer controlled. Two pieces of apparatus were used to measure it: a four-channel physiometer PHY-400 (Premed, Norway) and a four-channel dynograph R411 (Beckman, Germany; Figure 1). Analogue signals from those pieces of apparatus were digitized with the frequency of 2 kHz through a 12-bit analogue/digital transducer and sent to an IBM-compatible computer (66 MHz, 16 MB RAM).

The EMG signal was registered by two active surface electrodes placed along muscle fibers at a 2-cm distance from each other, according

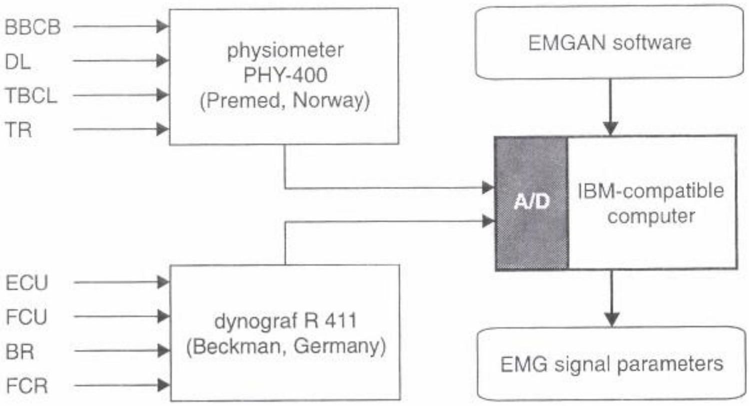

Figure 1. Block diagram of the measuring system. *Notes.* BBCB—biceps brachii caput breve, DL—deltoideus, TBCL—triceps brachii caput laterale, TR—trapezius, ECU—extensor carpi ulnaris, FCU—flexor carpi ulnaris, BR—brachioradialis, FCR—flexor carpi radialis, A/D—analogue/digital transducer, EMG—electromyography.

to typical procedure (Christensen, 1986b; Hägg & Suurküla, 1991; Kilbom, Gamberale, Persson, & Annwall, 1983). In order to keep the resistance of the skin-electrode below 2 kΩ, the skin was cleaned, the epidermis was removed, and Beckman conductive gel was used before the electrodes were attached.

2.3. Participants

Seven young, healthy men took part in the studies with constant load. The average age of those participants was 25 years (20–37 years), the average body mass was 77 kg (72–85 kg), and the average body height was 179.4 cm (171–193 cm).

There were 10 participants in the studies with intermittent load. The average age of those men was 22.5 years (18–26), the average body mass 73.7 kg (64–85 kg), and the average body height was 179.7 cm (171–191 cm).

For the purpose of theoretical calculations, the length of the arm, forearm, and hand were measured. The mass of those body parts was assessed using the Zatsiorsky formula (Zatsiorsky, Aruin, & Sieluyanov, 1981) on the basis of the whole body mass measurements.

2.4. Variants of Experiment

Experimental studies and calculations of muscle force for a given number of participants were performed for the same limb locations and the same values and directions of the external force. The results of the calculations were compared with the results from experimental studies. The engagement of the eight upper extremity muscles was examined (a) when the limb was loaded with its own load only and (b) when it was loaded with an additional external force, constant or intermittent. The muscle fatigue and load is influenced by the limb location, the vector of external force, and the frequency or duration of the load exertion. The theoretical model did not take into account the third of those factors, so it did not differentiate between intermittent and constant loads. However, work tasks at a real work stand usually have a more or less dynamic character, which results in different patterns of musculoskeletal load. That is why it was decided to perform an experimental study with an external force constant (conditions closer to the theoretical model) and intermittent (conditions closer to reality). This made it possible to compare and assess the model in relation to real conditions at a work stand. For theoretical model verification, 10 different limb locations were

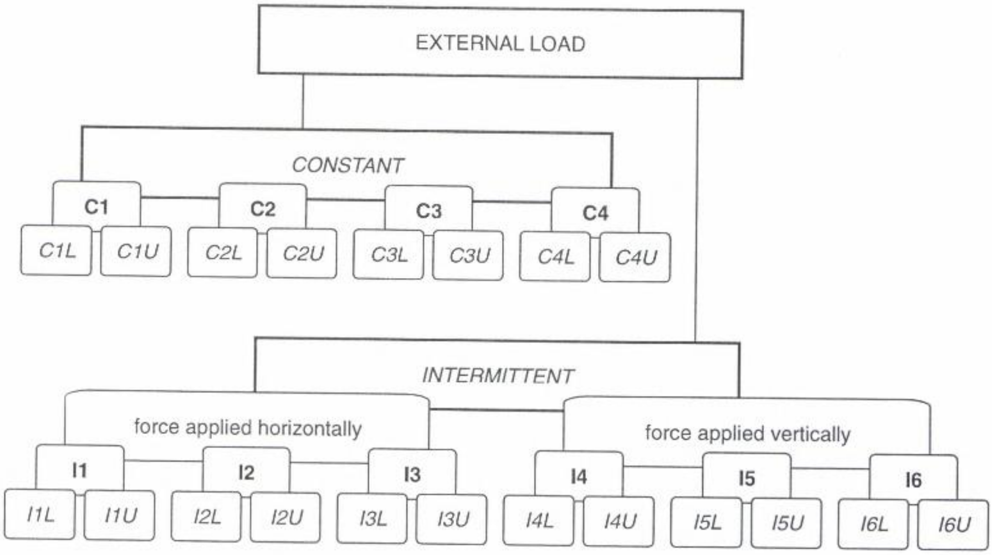

Figure 2. Diagram of experimental variants. *Notes.* I—studies with intermittent load, C—studies with constant load, L—variants with external force, U—variants without external force.

chosen—four for studies with constant load and six for studies with intermittent load (Roman-Liu, Wittek, & Kędzior, 1996). Therefore, there were muscle force calculations and experiments for 20 variants differentiated by the character of load, constant (C) or intermittent (I), and the value of external force, unloaded (U) or loaded (L, Figure 2).

In experiments without external force (U), muscular load was caused by the weight of the upper extremity only. In experiments with external force (L), muscular load was caused by the weight of the upper extremity plus a 1-kg disk held in the right hand (for studies with constant load) or by pushing a push-button with a force of 20 N four times per minute (10 s of pushing, 5 s of resting) for studies with intermittent load.

2.5. Experiment

EMG measurements were performed with a frequency of 2 times per minute during isometric muscle contraction. During the experiment, each participant kept his right upper extremity in a given position for the duration of the experiment. The left upper extremity hung down naturally, the spine and head were upright. The head and arm location were controlled by screening angles of the arm and head registered in two dimensions by correspondingly located transducers. The limb position was defined in terms of the angles between the trunk and the arm, the arm and the forearm, and the forearm and the hand in flexion/extension and abduction/adduction planes. Experiments with and without external force were performed for each limb location.

For each upper extremity location, measurements were conducted for variants with and without external force. Each experiment was divided into three parts: (a) keeping the arm in a given position for 15 min, (b) relaxing for 30 min, (c) keeping the upper extremity in a given position with an additional external load for 15 min.

In determining the duration of force exertion, the relationship between time and the percentage of Maximum Muscle Contraction (Corlett, 1990) and the results of the experiments of other researchers (Dieen, Toussaint, Thissen, & Ven, 1993; Hagberg & Hagberg, 1989) were taken into consideration. Recovery time was determined to be 30 min on the basis of studies showing that muscles recover after this time (Funderburgh, Hipskind, Welton, & Lind, 1974).

If a participant felt pain and was not able to keep his upper extremity in position for the determined time, he was allowed to finish the experiment early.

3. ANALYSIS OF THE REALATIONSHIP BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

3.1. Methods of Analysis

Analysis was performed to assess the correlation between the results of experimental studies (AMP and SZC) and calculations conducted on the basis of the computer model (MOD). Correlation was calculated for each examined muscle by the Spearman Correlation Coefficient and it was taken as statistically significant in those cases where the significance level was $p < .05$.

To examine if changes in the values of parameters from experimental studies are in step with parameters from theoretical studies, a differentiation of musculoskeletal load according to the value of the external force was conducted. Differences in the values of parameters (AMP, SZC, MOD) for variants with and without external force were assessed. The nonparametric Wilcoxon Sign Test was used to assess if the differences in the values of those parameters between variants with and without external force were statistically significant. For each analyzed muscle, a parameter called the Ratio of Load was calculated for every parameter (AMP, SZC, MOD). The Ratio of Load is a quotient of averaged values of analyzed parameters (AMP, SZC, and MOD) in variants with and without external force. Average values were calculated from 28 values in studies with constant load and from 60 values in studies with intermittent load (in each group, there were values of parameters for all participants and limb locations for each examined muscle). It was checked if the values of the Ratio of Load of the analyzed parameters for the examined muscles belonged to the same range, that is, if they were higher or lower than 1. If the Ratio of Load for all three parameters belonged to the same range, it was assumed that there was agreement between theoretical and experimental results.

3.2. Results

The results of correlation analysis are presented in Figures 3 and 4. Figure 3 presents the values of coefficients of correlation between forces in muscles calculated by the theoretical method (MOD) and muscle tension calculated by the experimental method (AMP). There is statistically significant correlation for TR, FCU, FCR, and DL (excluding variants without external force in studies with constant force). For muscle BBCB, there is statistically significant correlation only for studies with intermittent load for variants with external force. For other muscles, that is, for TBCL, ECU, and BR correlation coefficients are not statistically significant in any of the variants.

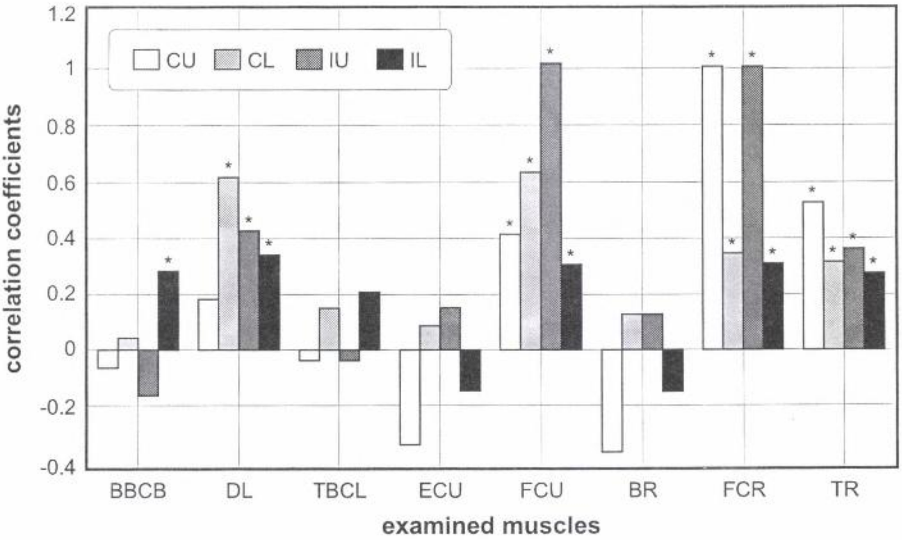

Figure 3. Values of coefficients of correlation between parameters MOD and AMP. *Notes.* MOD—muscle forces calculated by the computer model, AMP—amplitude calculated as Root Mean Square, BBCB—biceps brachii caput breve, DL—deltoideus, TBCL—triceps brachii caput laterale, TR—trapezius, ECU—extensor carpi ulnaris, FCU—flexor carpi ulnaris, BR—brachioradialis, FCR—flexor carpi radialis, C—study with constant load, I—study with intermittent load, U—variants without external force, L—variants with external force, *—differences statistically significant at $p < .05$.

Figure 4 presents coefficient values of correlation between parameters MOD and SZC. In most cases, the values are low. Correlation coefficients for muscles FCU and FCR are exceptions. In variants without external load, in three out of four cases the correlation coefficient values for those muscles are 1, which shows that there is very strong correlation between parameters MOD and SZC. This correlation is probably strictly connected with the fact that for those cases parameter MOD was calculated as equal to zero. For muscle FCU, the correlation coefficient for studies with constant load in variants without external force is not statistically significant.

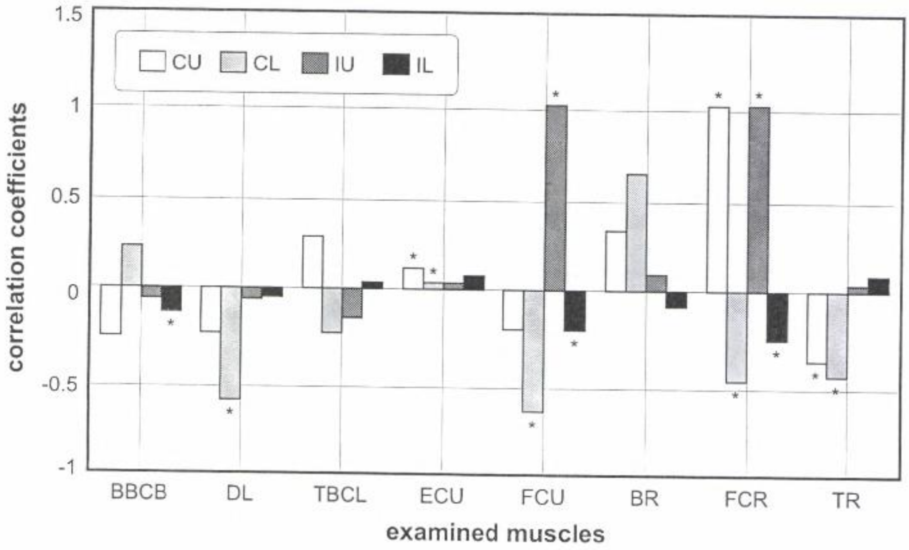

Figure 4. Values of coefficients of correlation between parameters MOD and SZC. *Notes.* MOD—muscle forces calculated by the computer model, SZC—coefficient of the slope of the regression line between time and Zero Crossing values, BBCB—biceps brachii caput breve, DL—deltoideus, TBCL—triceps brachii caput laterale, TR—trapezius, ECU—extensor carpi ulnaris, FCU—flexor carpi ulnaris, BR—brachioradialis, FCR—flexor carpi radialis, C—study with constant load, I—study with intermittent load, U—variants without external force, L—variants with external force, *—differences statistically significant at $p < .05$.

For muscles TBCL and BR, correlation coefficients are not statistically significant for any of the four cases, that is, for variants with and without external force in studies with constant and with intermittent load. For muscle TR, correlation coefficients are statistically significant for studies with constant load.

Figure 5 presents values of the Ratio of Load for MOD, AMP, and SZC in studies with constant load. Statistically significant differences accrued in 22 out of 24 cases. In two cases (for ECU and BR), results from model calculations show that the average value for MOD, which is proportional to forces in muscles, in variants with external force was lower than in variants without external force, which is not in step with experimental results. All other values of the Ratio of Load are higher than 1, which means that average values of analyzed parameters in variants with external force are higher than in variants without it. There are high values of the Ratio of Load for muscles FCU and FCR, specially for parameters MOD and SZC. For all muscles, the Ratio of Load for SZC, which characterizes muscle fatigue, is higher than for the amplitude of the EMG signal (AMP). In the case of muscle FCR, the average value of parameter MOD is equal to zero, which gives an undetermined value of the Ratio of Load for this parameter.

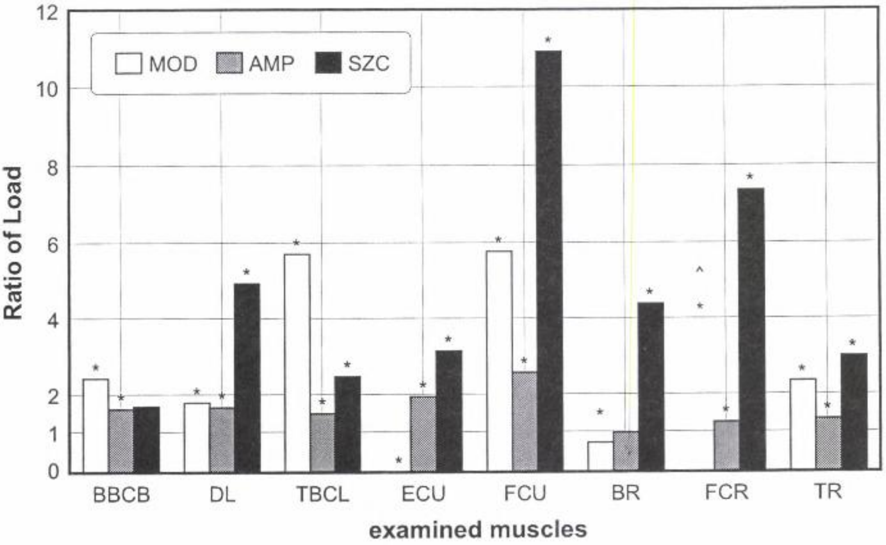

Figure 5. Values of the Ratio of Load for eight examined muscles for parameters MOD, AMP, and SZC from studies with constant load. *Notes.* MOD—muscle forces calculated by the computer model, AMP—amplitude calculated as Root Mean Square, SZC—coefficient of the slope of the regression line between time and Zero Crossing values, BBCB—biceps brachii caput breve, DL—deltoideus, TBCL—triceps brachii caput laterale, TR—trapezius, ECU—extensor carpi ulnaris, FCU—flexor carpi ulnaris, BR—brachioradialis, FCR—flexor carpi radialis, *—differences statistically significant at $p < .05$, ^—values indeterminable.

In experiments with intermittent load, there are statistically significant differences in 20 out of 24 cases (Figure 6). For parameter AMP, there are statistically significant differences for all muscles. In three cases, there are no statistically significant differences for parameter SZC.

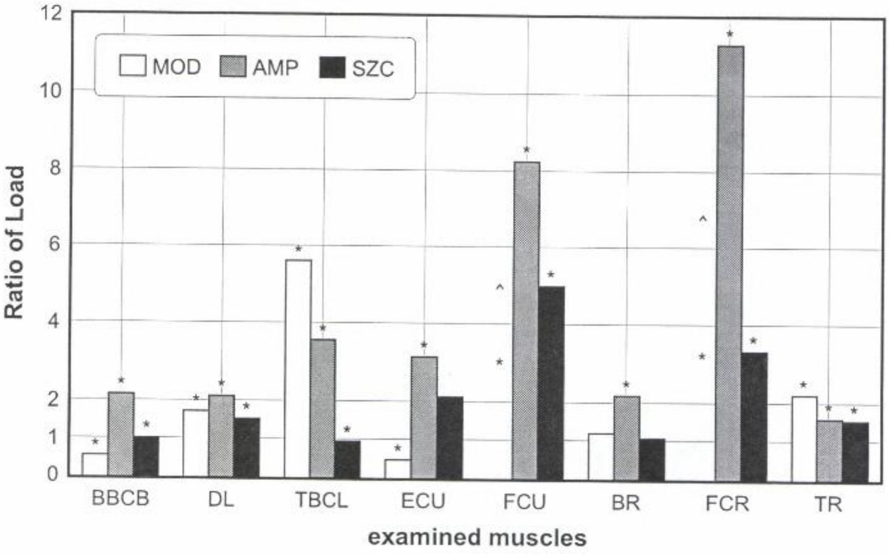

Figure 6. Values of the Ratio of Load for eight examined muscles for parameters MOD, AMP, and SZC from studies with intermittent load. *Notes.* MOD—muscle forces calculated by the computer model, AMP—amplitude calculated as Root Mean Square, SZC—coefficient of the slope of the regression line between time and Zero Crossing values, BBCB—biceps brachii caput breve, DL—deltoideus, TBCL—triceps brachii caput laterale, TR—trapezius, ECU—extensor carpi ulnaris, FCU—flexor carpi ulnaris, BR—brachioradialis, FCR—flexor carpi radialis, *—differences statistically significant at $p < .05$, ^—values indeterminable.

For muscle BBCB, the ratio for MOD is lower than 1, whereas values for EMG parameters values are higher than 1. A similar situation occurs for muscle ECU. For two muscles—FCU and FCR—for variants without external force averaged values of MOD are equal to zero, so the calculation of the Ratio of Load was not possible (undetermined value). There are higher values of the Ratio of Load for parameter AMP than for parameter SZC.

4. DISCUSSION

Correlation between parameters that characterize musculoskeletal load in theoretical and experimental studies was examined. Agreement and disagreement between parameters obtained by differences of musculoskeletal load according to the value of external force were also analyzed.

In most cases, there is statistically significant correlation between EMG parameters from experimental studies and the value of parameter MOD proportional to muscle forces calculated by the computer model. Values of the MOD parameter are better correlated with the amplitude value of the EMG signal (AMP) than with the parameter that reflects muscular fatigue (SZC). This is true for both studies with constant and with intermittent load. However, in studies with constant load, coefficients of statistically significant correlation between MOD and SZC occur in a greater number of cases than in experiments with intermittent load. This is probably due to higher muscular fatigue in experiments with constant load, which creates a stronger interdependence between muscle tension and muscle fatigue.

Experimental and theoretical results can be regarded as in step for four muscles: FCR, FCU, DL, and TR. For studies with constant load, correlation between parameters AMP and MOD—and also between SZC and MOD—was shown for those muscles. For studies with intermittent load, for muscles DL and TR, there was no correlation between parameters SZC and MOD, whereas there was correlation between AMP and MOD. This also shows that the dependence between the amplitude of the EMG signal and the fatigue parameter is stronger for studies with constant than with intermittent load. Therefore, in the case of studies with constant load for four muscles (DL, TR, FCU, and FCR), it can be said that there is convergence between the results of theoretical and experimental studies. This relationship is weaker in experiments whose conditions were closer to a real work stand (experiments with intermittent load). This is caused by the fact that the theoretical model does not take into account processes connected with the duration of work and the frequency of repetitions.

There is lack of strong correlation between the results of theoretical and experimental studies for muscles BBCB, TBCL, ECU, and BR. In studies with intermittent load, the values of coefficients of correlation between MOD and EMG parameters for muscle BBCB are statistically significant only for variants with external force and, additionally, the values of the correlation coefficients are low (lower than .5). For muscle BR, in studies with constant load none of the coefficients of correlation between theoretical and experimental studies is statistically significant and there are unexpected correlation coefficients (below zero for AMP and above zero for SZC). This suggests that there are some disagreements between theoretical and experimental studies. On the basis of theoretical calculations, it can be stated that for BBCB, ECU, and BR there were higher muscular forces in variants without external force than in those with external force.

There is agreement between theoretical and experimental results in differentiation according to the value of the external force. For EMG parameters, all values of the Ratio of Load are higher than 1 in both studies with constant and with intermittent load, although not all differences are statistically significant. Results of the study with constant load indicate that, generally, values of the Ratio of Load are lower for MOD and AMP than for SZC. In studies with intermittent load, on the contrary, the values of the Ratio of Load for MOD and AMP are higher than for the fatigue parameter SZC. Most probably this proves that muscular fatigue in experiments with constant load is higher than in studies with intermittent load, despite the lower value of the external force. Values of the Ratio of Load for MOD are similar to values for amplitude (AMP). However, it should be noted that in studies with constant load, values of the Ratio of Load for MOD are higher than for AMP, whereas in studies with intermittent load, the Ratio of Load for MOD has lower values than for AMP.

Values of the Ratio of Load for parameter MOD are lower than 1 for muscle ECU in studies with constant and with intermittent load, for muscle BR in studies with constant load, and for BBCB with intermittent load. This suggests that for those muscles there are some inaccuracies in model, which is in step with the described earlier results of correlation analysis. This analysis showed that for ECU, BBCB, and BR there is no correlation between theoretical and experimental results. Therefore, for muscles for which there is no correlation between values of muscle forces (MOD) and of EMG parameters there are also discrepancies in studies of the differences of muscular load according to external force.

For four muscles (DL, FCU, FCR, and TR), differences shown by values of the Ratio of Load are statistically significant for all analyzed parameters; coefficients of correlation between EMG parameters and MOD for those muscles are in most cases statistically significant, too. Hence, it can be accepted that the model describes those muscles correctly.

There is agreement in differentiation according to the value of external force. Analysis of correlation between EMG parameters and simulation results also indicates partial agreement between parameters from theoretical calculations and from experimental studies. Such agreement occurs for four out of eight examined muscles. In summary, it can be stated that theoretical and experimental results are not identical in correlation analysis, however, in comparative analysis (Ratio of Load), the agreement is much greater.

The lack of ideal agreement between theoretical and experimental results is most probably caused by both inaccuracies in the experimental method and simplifications in the model. Sources of dispersion in EMG studies are connected with subjective differences. Values of EMG parameters are to a high degree dependent on the kind of muscles and the contribution of fast and slow fibers (DeLuca, Sabbahi, & Roy, 1986; Fallentin, Sidenius, & Jörgensen, 1985; Gerdle, Wretling, & Henriksson-Larsen, 1988; Hagberg & Hagberg, 1989). Sources of discrepancies in theoretical calculations lie in not strict enough subjective differentiation and in too high simplification of the model (bones were taken as rigid links, muscles as lines, bone radius and ulna were modeled as one rigid link, shoulder girdle was not taken into account). The differences in results can also be caused by individual differences between people. Only limb mass and limb length were measured separately for each participant. Therefore, it can be stated that both the theoretical and experimental methods have some inaccuracies and should be considered as approximate.

It should be considered that out of the 34 muscles taken into account in the model, comparative analysis was conducted for 7 muscles only. That is why special attention should be paid to muscle TR as an indicator of whole shoulder load and to results of comparison of EMG parameter values for this muscle with the sum of all muscles in the upper extremity model. In this case, for studies with constant load, correlation coefficients are statistically significant for both AMP and SZC and their values are about .4. In intermittent load studies, there is no correlation between parameters SZC and MOD. In analysis according to external force, the Ratio of Load for MOD and EMG parameters belongs to the same range and all values are statistically significant, which means that for muscle trapezius there is strong agreement between theoretical and experimental studies.

On the basis of the analysis whose aim was to differentiate musculoskeletal load according to external force, it seems that in most cases the same differences were shown by theoretical and experimental methods in the same way. Agreement and discrepancy between the results of the theoretical and experimental studies were shown for the same muscles by correlation analysis and by analysis of differences of muscular load according to external force.

On this basis, a conclusion can be drawn that the developed program for work space optimization is good enough for this purpose. Thus, the model can be used for comparing musculoskeletal load for different limb locations and external force conditions, which means that it can be used for work place optimization.

Interdependence between theoretical and experimental results differs between studies with constant and intermittent load. This is especially clear in the case of the SZC parameter, which reflects muscle fatigue. Thus, a conclusion can be drawn that the kind of external load has a big influence on muscular fatigue and that it should be taken into account in the process of work space optimization. The developed method of work space optimization does not take into account processes in time connected with the work pattern. However, in those cases in which muscular fatigue is proportional to forces developed by muscles, the developed computer program can be used for work space optimization at a real work stand. It should be noted that for studies with constant load, there is agreement between parameters that express muscle force (MOD and AMP). This means that for static conditions this model is very precise in describing reality.

5. SUMMARY

In both theoretical and experimental studies, there is good differentiation of muscular load according to external force value. The lack of complete agreement between theoretical and experimental studies is caused by inaccuracies in the model and in experimental studies caused in both cases by the participants' subjective features. The developed method for work space optimization of the upper extremity can be used for tasks in which muscular fatigue induced by external load is proportional to forces developed by muscles. This method can be also used in other cases but the results should be considered as approximate.

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