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Upper Limb Load as a Function of Repetitive Task Parameters: Part 1—A Model of Upper Limb Load

Danuta Roman-Liu

Central Institute for Labour Protection – National Research Institute, Warsaw, Poland

*The aim of the study was to develop a theoretical indicator of upper limb musculoskeletal load based on repetitive task parameters. As such the dimensionless parameter, Integrated Cycle Load (*ICL*) was accepted. It expresses upper limb load which occurs during 1 cycle. The indicator is based on a model of a repetitive task, which consists of a model of the upper limb, a model of basic types of upper limb forces and a model of parameters of a repetitive task such as length of the cycle, length of periods of the cycle and external force exerted during each of the periods of the cycle.*

Calculations of the ICL *parameter were performed for 12 different variants of external load characterized by different values of repetitive task parameters. A comparison of* ICL*, which expresses external load with a physiological indicator of upper limb load, is presented in Part 2 of the paper.*

external load upper limb handgrip force cycle work repetitive task parameters

1. INTRODUCTION

Study results indicate that musculoskeletal disorders have their source in a mechanical overload of the body during the performance of work tasks. The causes of those disorders are too high levels of external forces and improper work techniques due to the performed task and connected with lifting loads, pushing, pulling and manipulation with heavy tools. However also work at workplaces where mostly upper limbs are involved in performing work tasks with static load of the back causes musculoskeletal disorders [1, 2].

Musculoskeletal disorders are determined by, among others, genetic, morphological, psychosocial and biomechanical factors. In each of those categories there are many variables whose occurrence determines musculoskeletal disorders. The first three groups of factors are individual and they relate to a given person. Psychosocial and biomechanical factors are external stimuli for a worker. Those factors describe work conditions and indirectly influence workers' musculoskeletal systems.

The main biomechanical factors which influence muscular load are external force, the location of body parts and the time factor. The time factor can be considered as the long lasting time of performing the same tasks day by day but also as exertion of a force in a given body position for a determined time. As the abovementioned biomechanical factors describe external load of the upper limb they should be analyzed jointly [3].

Work activities can be static or intermittent, which in this paper is described as a repetitive task. It is a repetitive task of the upper limb that causes stress and musculoskeletal disorders which are very frequent in workplaces today

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Correspondence and requests for offprints should be sent to Danuta Roman-Liu, Central Institute for Labour Protection – National Research Institute, ul. Czerniakowska 16, 00-701 Warszawa, Poland. E-mail: <daliu@ciop.pl>.

and which should be reduced [4]. Moreover, in such situations very often there is very high repeatability of sequences of moves. A problem connected with the assessment of upper limb musculoskeletal load at these kinds of workplaces arises. Several studies presented load of the upper limb assessed by physiological parameters dependent on parameters which described the performed repetitive task [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

Taking into consideration that experiments are expensive and time consuming there is a need to develop a theoretical indicator of upper limb load, which is based on parameters describing a repetitive task (repetitive task parameters) and express external load of a worker which comes from performed task. As external load has its source in parameters which describe the performed task, an indicator which expresses external load should present its value as a function of those parameters. Such an indicator should take into consideration force exerted by the upper limb at the workplace, the spatial characteristic of movement and the time characteristic of repetitive tasks in performing which upper limbs are involved. Such an indicator would make it possible to assess upper limb musculoskeletal load without the necessity to perform an experimental study, which would have broad effect in workstand optimization.

The aim of the study was to develop a theoretical indicator of upper limb musculoskeletal load based on repetitive task parameters. On the basis of a model of a repetitive task, which consists of a model of upper limb posture, a model of maximum forces and a model of a repetitive task indicator called Integrated Cycle Load (*ICL*), which expresses external load of upper limb, have been developed.

2. A MODEL OF UPPER LIMB POSTURE

Movements or location of body parts are usually described in relation to three planes: sagittal, frontal and transverse. Considering posture when the upper limb is in the anatomical position, movement in the sagittal plane forward is called flexion, backwards—extension, the frontal-plane movement in the direction of the body is called adduction, away from the body—abduction, rotation inside is called pronation and outside—supination.

As upper limb location plays a significant role in the capabilities of maximum force exertion, it is crucial to develop a system which would unambiguously define upper limb posture. From the biomechanical point of view the upper limb is a complicated mechanism, where three-dimensional location can be defined by at least seven angles describing upper limb posture in the form of flexion, extension, abduction, adduction, pronation and supination.

Upper limb location can be defined by seven angles on the basis of the Seven Degrees of Freedom Model, LIMB [16]. The model consists of an open kinematic chain with seven degrees of freedom with three rigid elements, which correspond to the arm, forearm and hand. It has been assumed that the trunk is immobile. According to the nomenclature applied in the theory of mechanics and mechanisms, joints are modelled as rotating kinematic pairs. For the shoulder joint it is a third-class kinematic pair (three degrees of freedom), for the elbow and wrist joint fourth-class (two degrees of freedom).

The model of the upper limb takes into account all the basic movements of the upper limb, defined in relation to the frontal plane—abduction/adduction; sagittal plane—flexion/extension, and pronation/supination defined as rotation round the axis of the limb. In the LIMB model, upper limb posture is determined by the values of seven angles. Flexion and extension are defined by the same angle, however, flexion angle values are positive whereas extension ones are negative. Similarly, abduction and adduction as well as pronation and supination. The accepted model of the upper limb is simplified as in reality the upper limb is considered as a mechanism of 27–30 degrees of freedom and seven degrees is the minimum which makes defining upper limb posture in space possible.

The range of values of the seven angles defining upper limb posture, which are related to work space, are as follows:

q_1—the angle of arm horizontal adduction/abduction (from 0^o to 90^o),
q_2—the angle of arm extension/flexion (from 0^o to 180^o),
q_3—medial/lateral rotation along the long axis of the arm (from -45^o to 45^o),
q_4—the angle of elbow flexion (from 0^o to 135^o),
q_5—the angle of forearm rotation pronation/supination (from -90^o to 90^o),
q_6—the angle of hand adduction/abduction (from -45^o to 30^o),
q_7—the angle of hand extension /flexion (from -80^o to 80^o).

3. MODELS OF BASIC TYPES OF FORCE

There are many different types of upper limb activities. The most common at the workplace are handgrip, pinch, lifting or carrying an object, pushing, supination and pronation.

The hand allows manipulation activities like handgrip, tip pinch, palmar pinch or lateral pinch. Handgrip as well as pinch are not only the most often used but they are also considered as the most objective tools for measuring the functionality of the upper limb. One of the basic types of force activities which occurs most often at the workplace is lifting connected with a mass of a hand-held tool as well as with force necessary for sustaining the upper limb in the determined posture. Lifting force is defined as a force exerted perpendicularly as a reaction to the force of gravity. Also, the force of pushing, i.e., force connected with the necessity of transversing any object horizontally, i.e., the force whose vector is parallel to the axis of the wrist, as well as the moment of force for supination and pronation are very often exerted at the workplace.

Many researchers [17, 18, 19, 20, 21, 22, 23, 24, 25, 26] have proved that upper limb posture influences maximum force. Therefore maximum force should be expressed as a function of the seven angles defining upper limb posture according to the Seven Degrees of Freedom Model (LIMB).

A model of maximum force for the basic types of force activities has been developed. To develop the model of maximal force for the handgrip force and pinch forces a meta-analysis was carried out. A predictive equation expressing the maximal force value as a function of seven angles describing upper limb posture was developed on the basis of the results published in various papers [27, 28]. A model of maximal forces for pushing, lifting, pronation and supination was developed on the basis of an experimental study performed by the author of the present paper [29]. The developed and presented in the abovementioned two publications predictive equations makes it possible to calculate maximum force for any upper limb posture defined by seven angles according to the LIMB model.

4. BOUNDARY UPPER LIMB POSTURE

Although force can be exerted during static conditions in a defined upper limb location, it can also be connected with the movement of the upper limb. Upper limb movement is performed according to the trajectory of movements, which can be defined by the posture of the upper limb in so-called Boundary Upper Limb Postures. It can be assumed that the trajectory between two Boundary Upper Limb Postures is optimal and repeatable for each individual person. Therefore, in determining force during movements only the Boundary Upper Limb Postures can be considered and force exerted during movement can be expressed as an average value of the force of the determined type exerted in the Boundary Upper Limb Postures.

5. PERIOD RELATIVE FORCE

Force can be considered as measured or assessed on the basis of the absolute value of force models (expressed, e.g., in Newtons, N). However it can also be expressed as relative force and such an attitude has been accepted in the presented model. Relative force expresses the ratio of exerted force (F) in relation to maximum force ($F_{\max}$) of the same type of the upper limb activity and the same upper limb posture. Relative force can be assessed as a percentage of the measured maximum force for the determined upper limb location. However force can also be measured for a defined upper limb posture and related to maximum force for the same upper limb posture calculated on the basis of a predictive equation. Usually a work task comprises a few upper limb activities performed at the same time. For example, using a drilling machine imposes on the operator exertion of a force which comprises of component forces like force connected with force exertion (pushing), force connected with the weight of the tool (lifting) as well as lifting force connected with the weight of the upper limb.

In repetitive work for each of the periods force, which consists of component relative forces, should be considered. Period Force is a parameter which presents—as a relative value—force, which is exerted during a period, considering all types of upper limb strength activities exerted during that period. Each of the component forces comprised in the Period Force is a relative force.

It was assumed that the force of the period can be expressed as a root square of the sum of squares of component relative forces as described by Equation 1:

$$PRF = \sqrt{(RF_1)^2 + \ldots + (RF_j)^2 + (RF_n)^2}, \qquad (1)$$

where PRF—Period Relative Force, RF_j—relative component force of the type of upper limb activity marked as j; $0 < j < n$; n—number of relative component forces.

Performing any task is connected with at least the necessity to lift the weight of the upper limb. However, usually forces like pushing or handgrip are exerted, too. Therefore, the simplest case of a general force is the sum of the component forces of supporting the upper limb in the defined posture and handgrip force, for example.

6. RELATIVE LIFTING FORCE RESULTING FROM THE WEIGHT OF THE UPPER LIMB

The weight of the upper limb is a component force in all of those upper limb activities where there is no support of the limb. Special attention should be paid to this type of force, thus it is necessary to develop a model of the force resulting from the weight of the upper limb. A good model of the force resulting from upper limb weight can be a model of some hand-held mass (weight). The question is how large the hand-held weight should be to be representative for upper limb weight. Mathiassen and Aminoff [30] presented a formula expressing glenohumeral torque of upper limb gravity force as equal to 0.024 multiplied by the weight of the participant's body and by the shoulder-wrist distance. On the basis on those studies it has been accepted that the lifting force, which expresses upper limb weight, can be modelled as a force of 2% of body weight held in the hand. Therefore the model of relative force supporting the upper limb in a determined posture (F_{suport}) can be approved as a ratio of gravity force of upper limb mass which is equal to 2% of body mass and maximum lifting force (F_{lifting}) calculated for the same upper limb posture. In such an approach, the relative force resulting from the weight of the upper limb is expressed as the force of lifting, which changes according to upper limb posture.

A predictive equation expressing maximum lifting force in relation to upper limb posture has been developed in a model of the maximum lifting force [29]. The maximum lifting force can be calculated on the basis of Equation 2, where $q_1, \ldots, q_7$ are angles describing upper limb posture:

$$\begin{gathered} F_{\text{lifting}} = 5.5836\, F_1\, (\sin 0.13\, (q_4 + 565^{\circ}) \\ - 0.885)\, (\sin 1.2\, (q_2 + 20^{\circ}) - 3.05)\, (\sin 1.3 \\ (q_7 + 69^{\circ}) + 1.06)\, (\sin 1.6\, (q_1 + 50^{\circ}) + 4.2) \\ (\sin 3.7\, (q_5 - 30^{\circ}) - 10.333), \end{gathered} \qquad (2)$$

where $F_1 = 1 - 0.054 \sin q_6 - 0.31 \sin q_3 - 0.11 \sin^2 q_6 + 1.2 \sin q_3 \sin q_6 - 0.06 \sin^2 q_3$.

The predictive equation, which makes it possible to calculate the maximum lifting force, was developed on the basis of the results of the experimental study performed on a group of participants of average body weight of 717.13 N. It means that the force of supporting the upper limb in a determined posture can be calculated on the basis of Equation 3:

$$F_{\text{suport}} = 14.34\ [\text{N}]/(F_{\text{lifting}} - 14.34)\ [\text{N}], \quad (3)$$

where F_{suport}—relative force of supporting the upper limb in a determined posture, F_{lifting}—maximum lifting force for a determined upper limb posture.

7. AN INDICATOR OF UPPER LIMB LOAD

A repetitive task imposes on the worker performing similar cycles for a determined duration of work. The similarity of cycles is considered in time sequences, exerted forces and three-dimensional characteristics of movements. The basic step in the assessment of the external load of a repetitive task is to develop a model to define the biomechanical parameters that describe a performed task.

Mathiassen and Winkiel [31] defined repetitive work with cycle duration, duration of exercise, duration of pause and the load during the exercise period.

Such a model considers a simple task with active and non-active periods and can be described with Figure 1a. A more general model usually demands activity for the whole cycle, but for each period there are different levels of load and different upper limb postures. Additionally, apart from the load resulting from a repetition of tasks, there can also be static load. A diagram of a repetitive task with a static-load component is presented in Figure 1b. There is also a possible repetitive task with an additional basic cycle (Figure 1c).

The most general model of a repetitive task considers both static load and a basic cycle and usually demands activity during the whole cycle, which means that there is a cycle task of

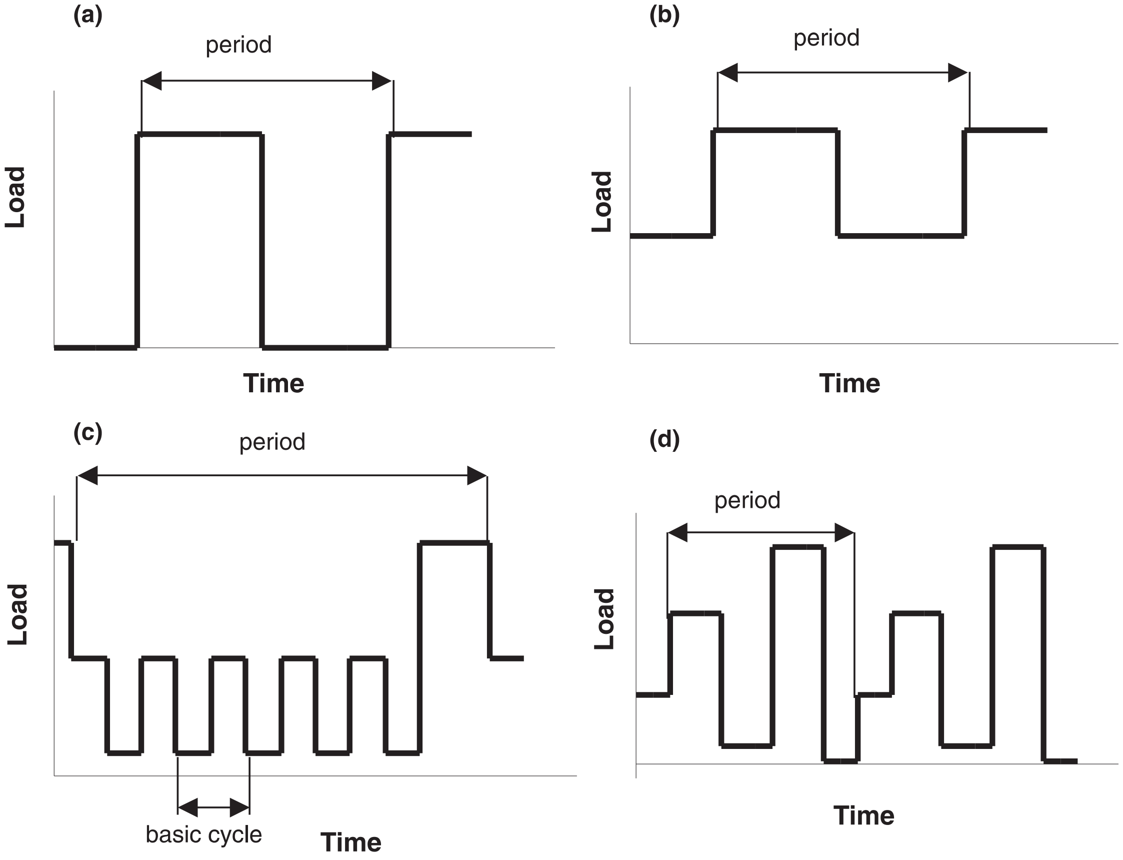

Figure 1. Examples of load during repetitive tasks.

a various number of cycle periods and various duration with different force levels (Figure 1d). This model accepts that during each period there is a different external force and a different upper limb posture.

In the model presented in this paper pause periods were skipped; all the periods were considered as exercise and they were marked with an appropriate index. In such an approach the repetitive task is characterized by the following repetitive task parameters: *CT*—cycle duration, *k*—number of periods, $0 < i < k$, DP_i—duration of *i*-th period, PF_i—external force of the *i*-th period.

According to the parameters proposed by Mathiassen and Winkiel [31], in the model of a repetitive task the pause period occurs only when the upper limb is supported and there is no external force. All activities are treated as the following periods of a cycle.

ICL was accepted as an indicator of the upper limb musculoskeletal load. This parameter expresses the upper limb load which occurs during one cycle. *ICL* (Equation 4) is calculated as the sum of *n* period forces (PF_i) multiplied by the duration of the relevant period (DP_i) divided by cycle duration (*CT*).

$$ICL = \frac{1}{CT}\sum_{i=1}^{n} DP_i \bullet PRF_i, \quad (4)$$

where *ICL*—Integrated Cycle Load, *CT*—cycle duration, *DP*—duration of a given period, *PRF*—external relative force of a given period, *n*—number of periods.

ICL is dimensionless; it expresses an area covered by the curve of external load during the successive periods of the cycle area shaded in Figure 2 divided by duration of the cycle.

8. EXTERNAL LOAD ASSESSED FOR SPECIFIC EXPERIMENTAL VARIANTS

ICL served as an indicator of external load in determined experimental conditions. An analysis of external load was performed for the study case. In this case external load was imposed by upper limb activity—a movement of the upper limb between two upper limb postures (Boundary Upper Limb Postures)—and exerting in those Boundary Upper Limb Postures handgrip force at a determined level. Upper limb load was determined by the location of the arm, forearm and hand, time sequences of the tasks included in the cycle (periods) and the force exerted in each

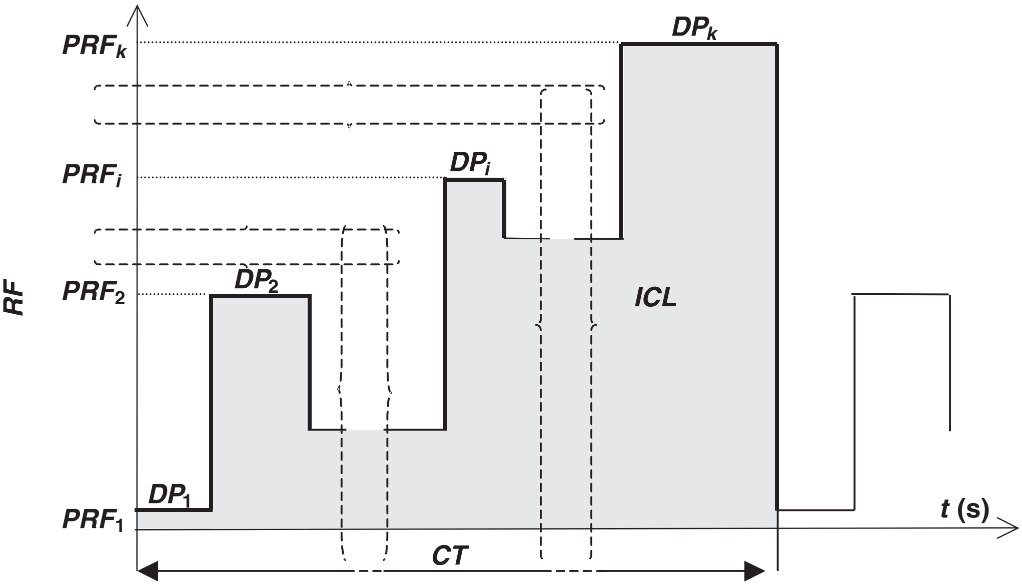

Figure 2. Illustration of Integrated Cycle Load (*ICL*). *Notes.* DP_i—duration of i-th period; PRF_i—relative force of period *i*; *i* = 1, 2, 3, 4; *CT*—cycle duration; *RF*—relative force.

period, which could be described by parameters of the repetitive task defined earlier.

Twelve variants of external load were considered. The main parameters describing variants of the load were the trajectory of movement defined by Boundary Upper Limb Postures and the value of the relative forces Period Force comprises of, i.e., handgrip force and the lifting force expressing upper limb weight.

The Boundary Upper Limb Postures were marked as Posture A, Posture B, Posture C and Posture D.

Posture A was the standard upper limb posture defined as seated with the shoulder adducted and neutrally rotated, the elbow flexed at 90^o, the forearm and wrist in the neutral position [23]. Although in postures B and C there was no abduction in the arm, it was flexed at 45^o. The angle between the arm and forearm was set to 135^o and there was supination of the forearm of 30^o. The wrist was in the neutral position. The difference between postures B and C consisted in the rotation of the arm around the axis. In posture B there was no rotation whereas in posture C there was rotation of 45^o. In posture D the upper limb was stretched forward with a full extension in the elbow.

The four Boundary Upper Limb Postures can be defined according to the Seven Degrees of Freedom Model as presented in Table 1.

The specific upper limb postures were chosen because they were significantly different from one another, and it was relatively easy to perform measurements and repeat the upper limb postures in subsequent experiments. Also while performing work task activities the selected upper limb postures are quite frequent.

One study cycle consisted of four periods, two periods of exerting handgrip force in a Boundary Upper Limb Posture and two periods connected with the movement of the upper limb between two Boundary Upper Limb Posture. The handgrip force, expressed as a relative force, exerted in given Boundary Upper Limb Postures was set up on the basis of maximum handgrip force measured before the experiment in the same upper limb posture (Table 2).

The duration of period 1 and period 3 imposed by the conditions of the experiment was set to 5 s, as the duration of periods 2 and 4 was set to 2.5 s.

TABLE 1. Values of Seven Angles Considered in the Study Defining Boundary Upper Limb Postures According to the Seven Degrees of Freedom Model

Boundary Upper Limb Postures	q_1	q_2	q_3	q_4	q_5	q_6	q_7
A	0^o	0^o	0^o	90^o	0^o	0^o	0^o
B	0^o	45^o	0^o	45^o	30^o	0^o	0^o
C	0^o	45^o	-45^o	45^o	30^o	0^o	0^o
D	0^o	90^o	0^o	0^o	0^o	0^o	0^o

TABLE 2. Characteristics of the Variants of the Experiments

Variants of Upper Limb Load	Boundary Upper Limb Postures	Relative Force of Handgrip (RF_{handgrip})
AC10	A–C	0.10
AB10	A–B	0.10
AD10	A–D	0.10
BC10	B–C	0.10
AC20	A–C	0.20
AB20	A–B	0.20
AD20	A–D	0.20
BC20	B–C	0.20
AC30	A–C	0.30
AB30	A–B	0.30
AD30	A–D	0.30
BC30	B–C	0.30

During periods of handgrip force (period 1 and period 3) the Period Relative Force (PRF_1 and PRF_3) was derived from the imposed one as 10, 20 or 30% of maximum handgrip force and the weight of the upper limb. During periods of movement (period 2 and period 4) the Period Relative Force (PRF_2 and PRF_4) came from the weight of the upper limb only.

In cases where movement of the upper limb was considered, that is, in periods 2 and 4 the mean value of the relative force of the supporting upper limb posture in the corresponding Boundary Upper Limb Postures was taken into consideration.

ICL was calculated according to Equation 4. Two types of component forces exerted while performing the task were taken into consideration.

Handgrip force was 10, 20 or 30% of maximum force depending on the experiment variant, which gave period 1 and period 3 relative force of the handgrip RF_{handgrip} equal to 0.1, 0.2 or 0.3.

A more complicated situation occurred for the relative force of supporting the upper limb in the defined upper limb posture. The first step to assess the force was to calculate the maximum lifting force according to Equation 2 for each of the four upper limb postures (A, B, C and D). Then, on the basis of Equation 3, the force of supporting the upper limb was calculated. Table 3 presents the maximum lifting force calculated for each of the four considered upper limb postures and the force of supporting the upper limb in the determined posture.

TABLE 3. Values of Maximum Lifting Force Calculated for the Four Examined Boundary Upper Limb Postures on the Basis of Equation 3

Boundary Upper Limb Posture	Relative Force of Upper Limb Support (RF_{suport})
A	0.078
B	0.130
C	0.107
D	0.144

Repetitive task parameters in each variant of experiment were determined on the basis of the model of a repetitive task as it is presented in Table 4.

Mean values and standard deviation for *ICL* calculated for each of the 12 variants of the experiment are presented in Table 5.

A comparison of *ICL* and the physiological parameters obtained as a result of the experimental study performed for the same 12 variants of external load is presented in Part 2.

TABLE 4. Values of Repetitive Task Parameters Which Define Variants of Upper Limb Load

	CT (s)	DP_1 (s)	$RF_{1\text{suport}}$	$RF_{1\text{handg}}$	PRF_1	DP_2 (s)	$PRF_2 = F_{2\text{suport}}$	DP_3 (s)	$RF_{3\text{suport}}$	$RF_{3\text{handg}}$	PRF_3	DP_2 (s)	$PRF_4 = F_{4\text{suport}}$
AC10	15	5	0.078	0.10	0.127	2.5	0.093	5	0.107	0.10	0.146	2.5	0.093
AB10	15	5	0.078	0.10	0.127	2.5	0.104	5	0.130	0.10	0.164	2.5	0.104
AD10	15	5	0.078	0.10	0.127	2.5	0.111	5	0.144	0.10	0.175	2.5	0.111
BC10	15	5	0.130	0.10	0.164	2.5	0.119	5	0.107	0.10	0.146	2.5	0.119
AC20	15	5	0.078	0.20	0.215	2.5	0.093	5	0.107	0.20	0.227	2.5	0.093
AB20	15	5	0.078	0.20	0.215	2.5	0.104	5	0.130	0.20	0.238	2.5	0.104
AD20	15	5	0.078	0.20	0.215	2.5	0.111	5	0.144	0.20	0.246	2.5	0.111
BC20	15	5	0.130	0.20	0.238	2.5	0.119	5	0.107	0.20	0.227	2.5	0.119
AC30	15	5	0.078	0.30	0.310	2.5	0.093	5	0.107	0.30	0.318	2.5	0.093
AB30	15	5	0.078	0.30	0.310	2.5	0.104	5	0.130	0.30	0.327	2.5	0.104
AD30	15	5	0.078	0.30	0.310	2.5	0.111	5	0.144	0.30	0.333	2.5	0.111
BC30	15	5	0.130	0.30	0.327	2.5	0.119	5	0.107	0.30	0.318	2.5	0.119

Notes. F_{suport}—relative force of sustaining upper limb in the defined upper limb posture; F_{handg}—relative handgrip force; CT—cycle duration; DP_i—duration of i-th period; PRF_i—relative force of period i; $i = 1, 2, 3, 4$.

TABLE 5. Values of Integrated Cycle Load (*ICL*) for Each Variant of the Experiment

Variant	*ICL*
AC10	0.113
AC20	0.171
AC30	0.235
AB10	0.138
AB20	0.191
AB30	0.251
AD10	0.104
AD20	0.164
AD30	0.228
BC10	0.153
BC20	0.202
BC30	0.261

10. SUMMARY

The aforementioned models of the upper limb, maximum forces and repetitive task parameters make it possible to determine external load which results from performing a repetitive task. External load of the upper limb can be expressed with *ICL*, which makes it possible to quantitatively assess the upper limb load resulting from performing work tasks. It is mostly used to compare different work activities.

The developed model allows quantitative assessment of the upper limb load as a function of parameters describing a performed task. *ICL* can be applied broadly in determining the external load of the upper limb for any performed task. It allows assessment and optimization of load, which results in a reduction of musculoskeletal load at the workstand.

The model was applied in verifying a hypothesis that *ICL*, which expresses external load imposed by work conditions, is proportional to the internal load of the upper limb assessed by physiological indicators.

The *ICL*, which expresses external load connected with performing a task, estimated for study cases was compared with the internal load of the upper limb assessed on the basis of the physiological reaction to the external load.

In paper *ICL* for 12 load variants is presented. Part 2 presents the results of an experimental study performed for the same variants of external load.

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