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# Force Weighting Approach To Calculate Spinal Cumulative Loading For Ergonomic Workforce Planning In Production

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**Abstract**

For the prevention of musculoskeletal disorders (MSD), the evaluation of manual materials handling (MMH) is important. In this context, cumulative loading can be used as an exposure index for the ergonomic assessment of workplaces. However, it was shown in previous empirical studies that most existing methods for calculating cumulative loading fail to completely capture the resulting physiological effects of working conditions on human workers. Therefore, this contribution outlines the development and validation of a novel force weighted approach to calculated spinal cumulative loading that reflects the muscular exposure. Empirical data from 36 individuals were used as the data basis for deriving and validating the calculation method. The results of the validation show a high prediction quality on the basis of the hold-out method. Hence, the method provides relevant indicators for the ergonomic assessment of MMH activities. Thus, it might be a useful tool for workforce planning in production.

**Keywords**

Ergonomics; Occupational Health; Industrial Engineering; Cumulative Loading; MSD; MMH

## 1. Introduction

Musculoskeletal disorders (MSD) are a relevant problem worldwide from both an economical and a societal point of view [1]. Moreover, there is empirical evidence which links work-related manual materials handling (MMH) to the occurrence of MSD [2]. Therefore, the assessment of work-related MMH is of central importance for maintaining the health of working humans and preventing work-related MSD in the context of workforce planning in production and manufacturing. In this context, Wells et al. [3] identify the spinal compression force as relevant exposure parameter and recommend the calculation of a cumulative spinal loading value as an exposure index. In essence, the approach of cumulative loading simultaneously considers both the intensity and the duration of the acting spinal compression force and is mostly extended by a weighting factor for the load intensity to account for empirical evidence that suggests a higher relative effect of the load intensity [4,5].

There are several methods for calculating cumulative loading which have in common that they are mostly based on the results of in vitro studies of material failure of human or animal specimens [6]. For regularly occurring work-related physical exposure, however, it has been shown that reversible physiological parameters, such as muscular activity, are much more relevant and should therefore be decisive instead of purely biomechanical limit values [7,8]. Indeed, in previous publications, it was shown that existing methods for calculating cumulative loading are not fully capable of capturing these reversible physiological reactions

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[6,9]. This applies in particular to the parameter muscular activity, which is widely recommended as an indicator for deriving measures in the context of ergonomic work design and workforce planning in production [4].
Consequently, empirical data on the relationship between spinal cumulative loading and reversible physiological reactions, such as muscular activity, are needed. On this basis, an evidence-based optimization of existing methods for calculating the cumulative load of MMH tasks can be derived. Such an optimized method would be a promising approach for ergonomic workforce planning in production. In this way, the data accumulating in the context of advancing digitization can be used to design the work environment in an economical and human-friendly manner by preventing work-related MSD while ensuring economical production. Therefore, the aim of this publication is to present a systematic analysis of the relationship between spinal cumulative loading and work-related muscular activity and, based on this, to develop and validate an optimized calculation method for the calculation of spinal cumulative loading for ergonomic workforce planning. Because of the specific relevance for practical use in occupational health [10], the range of medium intensity levels is focused.

## 2. Material and Methods

### 2.1 Participants

The empirical data used to derive the weighted calculation approach were collected in a laboratory study with 36 participants who were financially compensated for their participation. The required number of participants was determined in advance by statistical sample size planning in G*Power for a desired test power of 0.8. The study was approved by the Ethics Committee at the Medical Faculty of RWTH Aachen University (ID: EK 210/21). Participation was limited to individuals who did not currently have, or had not had in the 12 months prior to participation, any cardiovascular or musculoskeletal diseases or conditions. Persons aged 20 to 47 participated, 17 of them identified as male and 19 as female. In addition, age (mean = 25.7 years, SD = 4.9 years), height (mean = 174.8 cm, SD = 9.3 cm), and body weight (mean = 71.2 kg, SD = 12.0 kg) were recorded.

### 2.2 Empirical data base

The data base used to derive the weighted calculation approach consisted of three different runs of cyclic lifting activities. The load intensities analysed were of medium intensity [10]. The exact levels of external load were chosen so that each would have a different effect on the human body while excluding physical overexertion for individuals without cardiovascular or musculoskeletal diseases or conditions. For this purpose, an ergonomic risk assessment based on the method KIM-LHC (LMM-HHT-E) [11] was carried out in advance and as part of the application to the Ethics Committee.
During all lifting tasks, participants performed an identical two- dimensional, symmetric movement, which is shown in Figure 1, with an external load held in both hands. The trunk inclination was standardised to a range of 0° to 50° with the angle measured between the vertical line and the trunk longitudinal axis as shown in Figure 1. A stretched rope marked the lowest point of the movement. Touching the rope with the forehead signalled reaching of the lowest point. The arms were always perpendicular to the ground. The working pace was set to one lifting or lowering every three seconds and audibly signalled using a digital metronome. This working pace corresponds to a rate typical for occupational practice [12]. Participants completed a short practice session in order to familiarise with the task and pace. With the movement being identical, the three different runs of cyclic lifting activities differed in terms of the external load, as shown in Table 1. The movement was performed as described for 18 minutes in total. The individual lifting activities were each separated by a recovery break of 2 minutes. The participants spent each resting period sitting straight on a chair with the arms placed in the lap and the feet on the floor. The effectiveness in terms of muscular recovery of this resting period has already been shown [9]. The body posture of each participant was recorded at a

rate of 30 Hz using a Kinect sensor (Kinect V2, Microsoft, WA, USA). In the data analysis, the compression force of the intervertebral disc at L5/S1 was calculated for each frame using a biomechanical model validated for material handling in the sagittal plane [13]. As input data, body weight, body height and body posture were used.

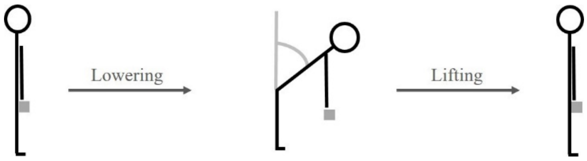


Figure 1: Symmetric MMH in the sagittal plane with marked trunk inclination angle. The arms were always held perpendicular to the ground and the external weight was always held in both hands.

Table 1: The three different runs of cyclic lifting activities that differ in terms of the external load held in both hands.

| Condition | External load |
|---|---|
| 1 | 2 kg |
| 2 | 4 kg |
| 3 | 6 kg |

With regard to the resulting muscular strain, bilateral muscle activity of the erector spinae longissimus (RES/LES) were collected. Since surface electromyography (EMG) is a suitable estimate for physical stress imposed by dynamic loads [14], the muscle activity was measured using EMG during the lifting/lowering task and the resting period. RES/LES was selected as a representative of the back muscles which are particularly strained during repetitive MMH [15]. To avoid disturbances of the EMG signal during the resting period, which was spent sitting, the chair was without a backrest.

### 2.3 Mathematical derivation of the force weighted calculation approach

Data from 30 individuals of the study described in 2.2 were used as estimation data to derive the weighting factor, and the remaining data were used as a test data set for validation. The characteristics of the estimation data set were as follows: 13 male and 17 female participants with a mean age (standard deviation) of 24.8 (2.5) years, a mean height of 175.2 (9.7) cm, and a mean body weight of 70.8 (12.2) kg.

The derivation of the equation for the force weighting factor $WF_{Force}$ was divided in two steps. First, based on the load intensity and the resulting muscular strain, an individual strain-load-ratio SLR was calculated by means of Equation (1). Here, the load intensity results from the maximum compressive load within an intensity level. The muscular strain results from the measured electrical muscular activity. The quantification of the electrical muscular activity is explained in detail in section 3. The strain-load-ratio SLR was calculated for each participant and intensity level for both RES and LES. Based on these individual values, average factors for each intensity level and both RES and LES were calculated. The calculation of factors is necessary to use literature-based factors for support points at the lower and upper edges. Since this empirical investigation focusses on the range of medium physical exposures, two additional data points were used in the minimum and maximum range: Following Parkinson & Callaghan [16], the empirically determined maximum compressive strength of the human spine of 6000 N [17] can be associated with a weighting factor of 30. As lower data point, 1 N is selected as a theoretical minimum load. Following empirical evidence from a previous in-vivo study on the relationship between spinal compression force on L5/S1 and electrical muscular activity, it can be stated, that an equivalent weighting of the risk factors load intensity and load duration are unsuitable even in the range of low spinal compression force [9]. Therefore, 1 N is associated with a force weighting factor of 1.01. Both additional, literature-based data points are shown in Table 2.

$$SLR_{Indicator,Intensity\ level} = \frac{Muscular\ strain_{Indicator,Intensity\ level}}{Load\ intensity_{Indicator,Intensity\ level}} \quad (1)$$

Based on the empirical data, the equation for the weighting factor was derived. The known points were plotted to a diagram and a mathematical description of the relationship between acting load and muscular strain was derived using the trend line function in Microsoft Excel 2016 (Microsoft Corporation, Redmond, Washington, USA). This procedure is equivalent to performing a non-linear regression and was chosen in accordance with other published studies [18–20].

Table 2: The two additional, literature-based data points used to derive the mathematical description of the relationship between acting load and calculated strain-load-ratio SLR.

| | | |
|---|---|---|
| x-axis [N] | 6000.00 | 1.00 |
| y-axis [-] | 30.00 | 1.01 |

## 2.4 Validation of the force weighted calculation approach

The hold-out method was used as a method of validation as previously described [21]. While data from 30 individuals of the study described in 2.2 were used as estimation data to derive the weighting factor, the remaining data of six participants were used as test data for validation. The characteristics of these participants were as follows: 4 male and 2 female participants with a mean age (standard deviation) of 30.5 (10) years, a mean height of 173 (6.8) cm, and a mean body weight of 72.7 (12.1) kg. This publication aims to derive an optimized force weighted calculation approach that reflects the muscular strain resulting from work-related MMH. In line with the methodological approach by Yazdanirad et al. [22], the validation was therefore performed as follows: The prediction quality of the new calculation approach was determined based on the correlation between values of the cumulative loading index calculated by means of the calculation method to be verified and the measured resulting muscular strain. For the interpretation of the correlation, a correlation from 0.1 is regarded as low, from 0.3 as medium and from 0.5 as strong [23].

## 3. Data analysis

To calculate the factors for the optimized calculation approach using Equation (1), both the load intensity and the resulting muscular strain are needed. To quantify the load intensity, the spinal compression force on the intervertebral disc at L5/S1 was biomechanically calculated based on body weight, external load and body posture, as explained in 2.2. Based on this, the maximum spinal compression force on L5-S1 was calculated for each participant and each intensity level (1, 2, 3). Since the movement is cyclic, the maximum compression force is constant within a participant and an intensity level, as shown in Figure 2.

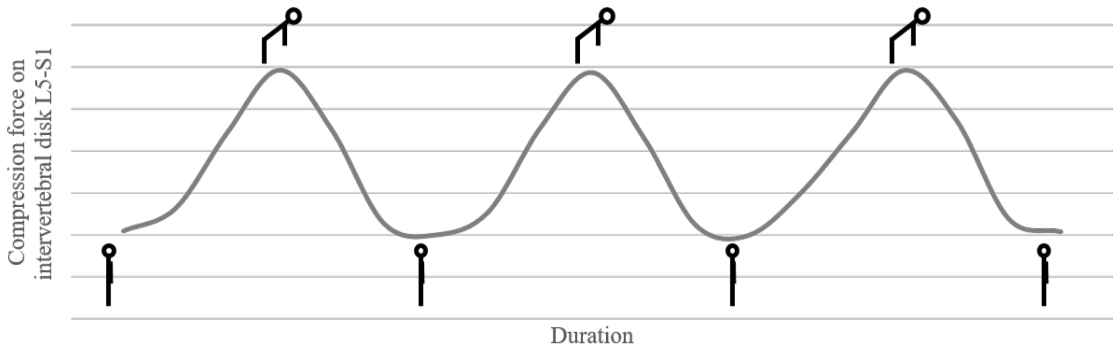


Figure 2: Schematic representation of the cyclic load with associated body positions at the maximum and minimum

To quantify the muscular strain, the area under the curve of the measured electrical muscular activity from RES and LES was determined. The calculation of the area under the curve was performed using the Noraxon MyoMuscle v3.14 software and the Integral calculation function. The resulting unit is thus %MVC • s. The calculation of the integral was chosen instead of an average value in order to represent the complete spectrum of the measured muscular activity.

Prior to the curve-fitting, paired t-tests were used to check whether the average factors over all participants of the estimation data set differed significantly between RES and LES. In case of no significant effect, further evaluation can be performed together for RES and LES. Statistical analyses were performed with IBM SPSS Statistics 28.0.1.0. Significance at the α-level of $p < .05$ was assumed. For the validation, Spearman's correlation coefficient was used, so the data do not need to be normally distributed [24].

## 4. Results

In this section, the general results regarding the acting load intensity and muscular strain, the calculated factors as well as possible differences between the body sides are presented (section 4.1). Based on both the empirically obtained and the literature-based data points, a new force weighted calculation approach is derived (section 4.2) and validated (section 4.3).

### 4.1 General results

Paired t-tests between RES and LES show no significant effect of body side on the strain-load-ratio SLR calculated using Equation (1). Average values of both the calculated maximum spinal compression force and the integral of the electrical muscular activity from RES and LES are shown in Table 3 and the resulting strain-load-ratio SLR are shown in Table 5. Statistics of the t-tests are presented in Table 4. Since the body side does not have a statistically significant effect on the calculated factors, a joint equation for the weighting factor $WF_{Force}$ is derived in the next step.

Table 3. Average values of both the calculated maximum spinal compression force and the integral of the electrical muscular activity from RES and LES. This data were used to calculated the ratios shown in Table 5.

| Level of intensity | Biomechanically calculated compression force on L5/S1 [N] | Integral of muscular activity [%MVC • s] | |
|---|---|---|---|
| | | RES | LES |
| 1 | 2495.44 | 7591.56 | 7444.90 |
| 2 | 2627.14 | 7983.01 | 8003.89 |
| 3 | 2792.25 | 8598.11 | 8620.40 |

Table 4. Results of the t-test within each intensity level between RES and LES for the strain-load-ratio SLR.

| Pair | Mean | Standard error of the mean | 95% confidence interval of difference | | t | df | p-value |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | | | |
| $SLR_{,RES,1} - SLR_{,LES,1}$ | .05 | .16 | -0.28161 | 0.38205 | .310 | 29 | .759 |
| $SLR_{,RES,2} - SLR_{,LES,2}$ | -.03 | .15 | -0.33985 | 0.27747 | -.207 | 29 | .838 |
| $SLR_{,RES,3} - SLR_{,LES,3}$ | -.02 | .15 | -0.32536 | 0.28239 | -.145 | 29 | .886 |

Table 5. Mean (± standard error) of strain-load-ratio SLR calculated using Equation (1).

| Body side | Level of intensity | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| RES | 3.16 ± .26 | 3.10 ± .23 | 3.15 ± .21 |
| LES | 3.11 ± .27 | 3.13 ± .24 | 3.17 ± .25 |

### 4.2 Derivation of forced weighted calculation approach

The resulting data on the relationship between acting maximum spinal compression load in L5-S1 and the strain-load-ratio SLR is shown in Table 6. The two additional data points, which were explained in 2.3, are also included.

Table 6. Points used to derive the mathematical description of the relationship between acting load and relative weighting factor. Since the evaluation is carried out jointly for RES and LES, the three values from the range of medium physical exposure obtained experimentally, are each listened twice.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x-axis [N] | 6000.00 | 2792.25 | 2627.14 | 2495.44 | 2792.25 | 2627.14 | 2495.44 | 1.00 |
| y-axis [-] | 30.00 | 3.15 | 3.10 | 3.16 | 3.17 | 3.13 | 3.11 | 1.01 |

The plotted data points are shown in Figure 3. With regard to the mathematical description of the relationship between acting load and relative weighting factor, an exponential curve has proven to be the most suitable for the following reasons: In the case of a polynomial function – as used previously [16] – the upper reference value of 6000 N and a factor of 30 would be in the curve, but there would be a global minimum in the range of 1000 N. This means that the weighting factor at 1000 N is lower than the fixed value of the lower guideline value 1.01 and for a load intensity around 1000 N the intensity is weighted lower relative to the load duration. This contradicts the empirical findings on the necessity of a relatively higher weighting of the load intensity to the load duration [4,5,9] and must therefore be avoided. The derived equation for the weighting factor $WF_{Force}$ is also shown in Figure 3 and its coefficient of determination is $R^2 = .97$.
This results in an optimized force weighted calculation approach for cumulative loading given in Equation 2 in accordance with the general form described by [16,25].

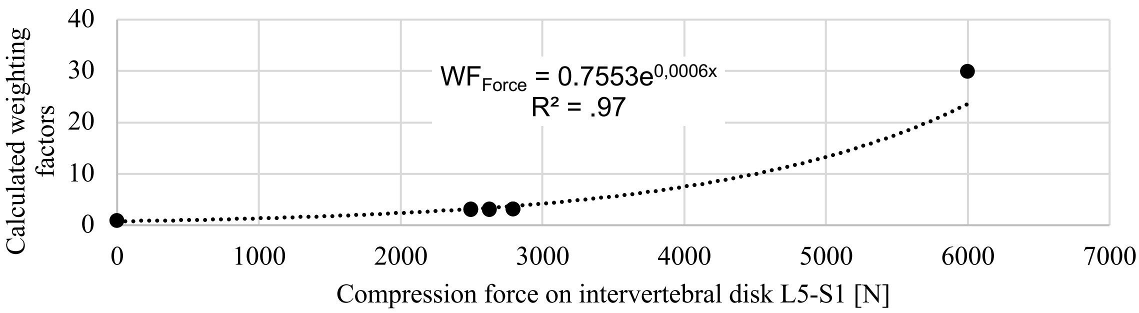


Figure 3. Plotted data points and resulting best-fitting curve to describe the relationship between acting load and load intensity weighting factor.

$$Cumulative\ loading = Exposure\ intensity\ \cdot WF_{Force}\ \cdot Exposure\ duration \qquad (2)$$

### 4.3 Validation of forced weighted calculation approach

The results of the correlation analysis are shown in Table 7. Since the correlation coefficient is above 0.5, the correlation between predicted and observed values can be classified as high according to [23].

Table 7. Result of the cross-validation for the evaluation of the forecast quality.

| Correlation between | Spearman correlation | p-value |
|---|---|---|
| Measured resulting muscular strain - Calculated cumulative loading | .799 | <.001 |

### 5. Discussion

The objective of this publication was the development and validation of a force weighted approach to calculate cumulative loading. The main motivation was the fact that existing calculation methods are mostly based on the principles of material failure when, in fact, physiological parameters, such as muscular activity, are much more relevant for workplace design for regularly occurring work-related physical exposure [7,8]. However, methods mainly based on the principles of material failure cannot adequately represent these particularly relevant parameters [6]. Therefore, an optimized calculation method based on a new force weighted approach was introduced. For the derivation of the optimized calculation method, the focus was placed on muscular activity, since this parameter is widely recommended as an indicator for measures in the context of ergonomic work design and workforce planning in production [4]. For this purpose, three levels of different load intensity where analyzed. Each level had a different effect on the human body, according to a preliminary ergonomic assessment. Due to additional literature-based upper and lower anchor points, the derived calculation method is also applicable for very high and very low load intensity.

The validation of the optimized calculation method shows very promising results. The prediction quality was determined based on the correlation between values of the cumulative loading index calculated by means of the calculation method to be verified and the measured resulting muscular strain. The results of the correlation analysis show a high correlation (cf. Table 7). For the optimized calculation method, this can be interpreted as a high prediction quality for capturing the physical exposure due to work-related manual lifting activities, and thus as a high quality for ergonomic assessment of physical exposure. As a conclusion of this validation, it can be stated that the overall objective, the optimization of existing methods for the calculation of an exposure index based on cumulative load for a better representation of physiological reactions, has been achieved.

With regard to possible limitations, the following aspect should be mentioned. Due to the literature-based anchor points for very high and very low load intensities, the optimized calculation method is applicable for the entire range from very low to maximum load with regard to the maximum compressive strength of the human spine. However, the calculation method developed here is not intended for exclusive use in the case of very high load intensity in the range of maximum strength of the human spine. If such high loads are present, a general improvement of the workplace to avoid such loads is advisable first, before cumulative loading should be used as a load index for further assessment. Furthermore, it must be mentioned that only a total of five levels of stress were used. Due to time restrictions with regard to the maximum duration of a laboratory study involving participants, it was not possible to investigate even more different levels within the scope of this study.

With regard to the upper anchor point, it must also be noted that the data point (6000|30) does not lie in the approximated curve of the derived calculation formula for the weighting factor $WF_{Force}$. However, it is also not necessary for the weighting factor to be exactly 30 at an applied compression load of 6000 N. This value

is derived by from experiments on material failure of porcine spine specimen [16]. Since the question of an exact transferability to human bodies still needs verification anyway, this value only serves as a guide value at this point as described. In contrast, it was considered extremely relevant to ensure that the calculated factor $WF_{Force}$ is always above 1. A value of 1 would in fact mean that the two factors load intensity and load duration are weighted equally. This becomes clear when inserting the value 1 in Equation 2. An equal weighting of the exposure factors load intensity and load duration contradicts empirical findings on a relatively higher influence of the load intensity compared to load duration [17,4,5]. Further empirical evidence also explicitly shows that an equivalent weighting of the factors load intensity and duration does not accurately reflect the resulting physical strain but underestimates the influence of higher load intensity [9]. The optimized calculation method presented in this paper takes into account these requirements and thus enables evidence-based ergonomic assessment for work-related MMH.
Furthermore, it should be noted that the optimized calculation method does not take into account any possible sex-specific differences. At the same time, the goal of the optimized calculation method is to better represent the physiological strain resulting from submaximal loading, for which no significant sex-specific differences are to be expected [26]. Moreover, this contribution focuses on the specific exposure case of MMH and the manual lifting activity performed to obtain the empirical data is a symmetrical, two-handed lifting activity. In order to realize a movement execution that is uniform across all test subjects, a very standardized activity was chosen. The derived optimized calculation rule is thus also based on a standardized, simple movement. Still, the derived optimized calculation method is therefore likely not fully suitable for the assessment of very different physical exposure. For example, static muscular work has a completely different effect on the human body than the dynamic muscular work studied here. At the same time, however, dynamic physical work is more frequently encountered in practice [10] and the great relevance of MMH with regard to the prevention of MSE was discussed at the beginning. With regard to other forms of dynamic, physical work that are practically relevant, pushing and pulling of loads can be mentioned [27]. Finally, it has to be noted that possible effects of fatigue were not included in the calculation approach. Since increasing fatigue is likely to have an influence on the muscular activity, further research might be useful with regard to working conditions of longer duration which may lead to physical fatigue.

## 6. Conclusion

This contribution outlined the development and validation of a calculation method for cumulative loading based on a newly derived force weighted approach. Based on empirical data of 36 individuals and further, literature-based data, a calculation approach was developed. Results of the validation show a high prediction quality for estimating the physical exposure due to work-related manual lifting activities, and thus as a high quality for ergonomic assessment of physical exposure. Further research is needed to extend the presented method to other forms of work-related exposure. Examples of other forms of physical stress that are practically relevant include pushing and pulling of loads.


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## References


[1] Maher, C., Underwood, M., Buchbinder, R., 2017. Non-specific low back pain. The Lancet 389 (10070), 736–747.

[2] Heneweer, H., Staes, F., Aufdemkampe, G., van Rijn, M., Vanhees, L., 2011. Physical activity and low back pain: a systematic review of recent literature. European spine journal : official publication of the European Spine Society, the European Spinal Deformity Society, and the European Section of the Cervical Spine Research Society 20 (6), 826–845.

[3] Wells, R., van Eerd, D., Hägg, G., 2004. Mechanical exposure concepts using force as the agent. Scandinavian journal of work, environment & health 30 (3), 179–190.

[4] Gallagher, S., Schall, M.C., 2017. Musculoskeletal disorders as a fatigue failure process: Evidence, implications and research needs. Ergonomics 60 (2), 255–269.

[5] Huangfu, R., Gallagher, S., Sesek, R., Schall, M., Davis, G., 2019. Evaluating the Effectiveness of Estimating Cumulative Loading Using Linear Integration Method, in: Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Springer International Publishing, Cham.

[6] Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2021. Comparison of Dose Models for the Assessment of Spinal Load and Implications for the Calculation of Cumulative Loading. Proceedings of the 21st Congress of the International Ergonomics Association, 93–100.

[7] Nussbaum, M.A., 2001. Static and dynamic myoelectric measures of shoulder muscle fatigue during intermittent dynamic exertions of low to moderate intensity. European journal of applied physiology 85 (3-4), 299–309.

[8] Waters, T.R., Putz-Anderson, V., Baron, S., 1998. Methods for assessing the physical demands of manual lifting: a review and case study from warehousing. American Industrial Hygiene Association journal 59 (12), 871–881.

[9] Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2022. Why cumulative loading calculated using non-weighted integration may not be suitable for assessing physical stress of the lower back: an empirical investigation of strain during lifting and lowering tasks. Ergonomics 65 (1), 134–146.

[10] Veerasammy, S., Davidson, J.B., Fischer, S.L., 2022. Multi-task exposure assessment to infer musculoskeletal disorder risk: A scoping review of injury causation theories and tools available to assess exposures. Applied Ergonomics 102, 103766.

[11] Steinberg, U., 2012. New tools in Germany: Development and appliance of the first two KIM ("lifting, holding and carrying" and "pulling and pushing") and practical use of these methods. Work (Reading, Mass.) 41 Suppl 1, 3990–3996.

[12] Marras, W.S., Parakkat, J., Chany, A.M., Yang, G., Burr, D., Lavender, S.A., 2006. Spine loading as a function of lift frequency, exposure duration, and work experience. Clinical Biomechanics 21 (4), 345–352.

[13] Jäger, M., Luttmann, A., 1989. Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment human model. Ergonomics 32 (1), 93–112.

[14] Dolan, P., Kingma, I., van Dieen, J., Looze, M.P. de, Toussaint, H.M., Baten, C.T., Adams, M.A., 1999. Dynamic forces acting on the lumbar spine during manual handling. Can they be estimated using electromyographic techniques alone? Spine 24 (7), 698–703.

[15] Dolan, P., Adams, M., 1998. Repetitive lifting tasks fatigue the back muscles and increase the bending moment acting on the lumbar spine. Journal of Biomechanics 31 (8), 713–721.

[16] Parkinson, R.J., Callaghan, J.P., 2007. The role of load magnitude as a modifier of the cumulative load tolerance of porcine cervical spinal units: Progress towards a force weighting approach. Theoretical Issues in Ergonomics Science 8 (3), 171–184.

[17] Brinckmann, P., Biggemann, M., Hilweg, D., 1988. Fatigue fracture of human lumbar vertebrae. Clinical Biomechanics 3, i-S23.

[18] Afolabi, H.K., Nordin, N.A.H., Nasef, M.M., Harun, N.Y., Ting, T.M., Saeed, A.A.H., 2021. Isotherms for adsorption of boron onto new fibrous adsorbent containing glycidol ligands: linear and nonlinear regression methods. IOP Conf. Ser.: Earth Environ. Sci. 842 (1), 12032.

[19] Agrawal, R., Whalley, R.D., Ng, H.C.-H., Dennis, D.J.C., Poole, R.J., 2019. Minimizing recalibration using a non-linear regression technique for thermal anemometry. Exp Fluids 60 (7).

[20] Jakobek, L., Matić, P., Kraljević, Š., Ukić, Š., Benšić, M., Barron, A.R., 2020. Adsorption between Quercetin Derivatives and β-Glucan Studied with a Novel Approach to Modeling Adsorption Isotherms. Applied Sciences 10 (5), 1637.

[21] Dankaerts, W., O'Sullivan, P., Burnett, A., Straker, L., Davey, P., Gupta, R., 2009. Discriminating healthy controls and two clinical subgroups of nonspecific chronic low back pain patients using trunk muscle activation and lumbosacral kinematics of postures and movements: a statistical classification model. Spine 34 (15), 1610–1618.

[22] Yazdanirad, S., Khoshakhlagh, A.H., Habibi, E., Zare, A., Zeinodini, M., Dehghani, F., 2018. Comparing the Effectiveness of Three Ergonomic Risk Assessment Methods-RULA, LUBA, and NERPA-to Predict the Upper Extremity Musculoskeletal Disorders. Indian journal of occupational and environmental medicine 22 (1), 17–21.

[23] Cohen, J., 1988. Statistical power analysis for the behavioral sciences, 2nd ed. ed. L. Erlbaum Associates, Hillsdale, N.J, 1 Online-Ressource.

[24] Field, A., 2018. Discovering statistics using IBM SPSS statistics, 5th edition ed. SAGE, Los Angeles, London, New Delhi, Singapore, Washington DC, Melbourne, 1070 pp.

[25] Zehr, J.D., Tennant, L.M., Callaghan, J.P., 2019. Examining endplate fatigue failure during cyclic compression loading with variable and consistent peak magnitudes using a force weighting adjustment approach: An in vitro study. Ergonomics 62 (10), 1339–1348.

[26] Daugherty, S.L., Magid, D.J., Kikla, J.R., Hokanson, J.E., Baxter, J., Ross, C.A., Masoudi, F.A., 2011. Gender differences in the prognostic value of exercise treadmill test characteristics. American heart journal 161 (5), 908–914.

[27] BAuA, 2019. Erweiterte Leitmerkmalmethode zur Beurteilung und Gestaltung von Belastungen beim Ziehen und Schieben (LMM-ZS-E): Entwurf zur Praxiserprobung, 12th ed. BAuA/ASER, Dortmund.

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