Simulation model for evaluation of ergonomic load in the use of exoskeletons

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Abstract. For the analysis of musculoskeletal workload and associated potential hazardous working conditions as well as musculoskeletal symptoms in worker populations among various occupations different approaches are taken, and extensive data collection studies are being accomplished. Questions are targeted on musculoskeletal workload and associated potentially hazardous working conditions can be categorized into seven indices (force, dynamic and static load, repetitive load, climatic factors, vibration and ergonomic environmental factors). Evaluation focus on standing, sitting, walking and uncomfortable postures, the indices constitute a brief overview of the main findings on musculoskeletal workload and associated potentially hazardous working conditions. The validity of the findings is fair when compared with an index of psychosocial working conditions and discomfort during exposure to physical loads. Worker groups with contrasting musculoskeletal loads can be differentiated on the basis of the indices and other factors. It appears that most indices and factors show significant associations with low back and/or neck-shoulder symptoms. This simulation model NIOSH analysis can be used as a simple and quick approach to identify worker groups in which a more thorough ergonomic analysis indicates possible improvements in load factor using particular exoskeletons at work.

1. Introduction

Underestimation of employers' ergonomic factors increases not only the physical, but also the mental and emotional load on employees, and thus the possibility of reducing reliability, performance, increased risk of accidents, occupational diseases and generally illness [1]. It is obvious, that factors influence the human separately or in combination as a number of factors together within the work system. This ultimately reflects the need for a holistic approach to ergonomics. Factors can be considered as ergonomic stressors and risks, which endanger human behavior, health, productivity, comfort, safety and quality at work [2]. Authors [3] provided an overview of assistive exoskeletons that have specifically been developed for industrial purposes in order to assess the potential effect of these exoskeletons on reduction of physical loading on the body. The search covers effects of different industrial exoskeletons, active (actuated) and passive (non-actuated). The effect on physical loading has been evaluated, mainly in terms of muscle activity for exoskeletons, all passive exoskeletons were aimed to support the low back. Results noticed reductions in back muscle activity during dynamic lifting and static holding.
Based on the Industry 4.0 paradigm, human-robot collaboration is widely investigated to relieve the human operator from non-ergonomic, and repetitive actions. Solutions, identified from the state of the art, can be seen in collaborative robots mostly for repetitive actions and wearable robots as more flexible solution for added-value operations [3-5]. Many solutions have been developed to empower and assist the human operator, varying from upper limbs exoskeletons to lower limbs exoskeletons and whole-body exoskeletons [6]. In order to solve the issue related to back-pain disorders, back-support exoskeletons represent the optimal solution in order to correctly redistribute the spinal load, improving the ergonomics while relieving the human operator from the load [3] [6]. Load manipulation and its risk influence on lower back can be assessed by simulation software Jack NIOSH analysis, so we can estimate workers’ group for using the back supporting exoskeleton.

2. Health and safety legislation

In the case of manual handling of an employee with loads, the employer must, as a standard in the Slovak Republic, follow Act no. 124/2006 Coll. on safety and health protection at work [7], as well as the supplementary Regulation of the Government of the Slovak Republic no. 281/2006 Coll. on the minimum safety and health requirements for the manual handling of loads [8]. These are subject to EU legislation Council Directive of 29 May 1990 on the minimum health and safety requirements for the manual handling of loads where there is a risk particularly of back injury to workers (fourth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC [9]) - (90/269/EEC [10]). Musculoskeletal disorders are the most common cause of severe long-term pain and incapacity for work. Not only do they cause personal suffering and loss of income, but they also represent significant costs for businesses and national economies. It is estimated that there are about 400 million people worldwide whose daily lives are limited and disadvantaged precisely because of reasons caused by work, handling loads and unhealthy lifestyles. Joint diseases (osteoarthritis, rheumatoid arthritis) account for almost half of all chronic diseases in people over 65 years of age. As many as 40% of women over the age of 50 suffer from osteoporotic fractures, and spinal diseases are the second most common cause of incapacity for work. Work-related musculoskeletal disorders are damage to the body structure, e.g. muscles, joints, tendons, ligaments, nerves, bones and the localized system of blood circulation, caused or worsened in particular by the work and the environment in which the work is performed. These injuries most commonly affect the back, neck, shoulders and arms, but can also affect the legs. Some of them, such as carpal tunnel syndrome in the wrist, are specific due to their well-defined signs and symptoms [11]. Others are non-specific because they manifest themselves only as pain or discomfort without evidence of a clear specific disorder. The diseases mentioned include disorders of the neck and upper limbs, which are the result of the sudden application of extreme force, most of which are caused by the effects of frequent repeated application of relatively little force over a long period of time. Different groups of factors can contribute to musculoskeletal disorders, including physical and biomechanical factors, organizational and psychosocial factors, individual and personal factors, which may occur alone or in various combinations. Although these diseases are on the rise, they can be prevented by evaluating work, introducing preventive measures and monitoring the effectiveness of the measures in place, as well as promoting a healthy lifestyle. [7-9]

Council Directive 89/391/EEC [7] [9] on the introduction of measures to encourage improvements in the safety and health of workers at work oblige the employer to eliminate the hazards and the resulting risks, to adapt the work to the employee's abilities and technical progress, to take into account human abilities, characteristics and possibilities, especially in workplace design, work equipment selection, work procedures and production processes to eliminate or mitigate work and monotonous work on the health of the employee, and the like. Council Directive 90/269/EEC on the minimum health and safety requirements for the manual handling of loads where there is a risk particularly of back injury to workers [8] [10] lays down minimum requirements for the safety and health protection of workers in the manual handling of loads where there is a risk of damage to health, in particular the spine of workers, and for preventing this risk, which is the assessment of the health condition of employees for manual handling of loads, taking into account the individual risk factors
listed in Annex 3 and the indicative mass values given in Annex 2. Inadequate working environments, such as poor workplace layout, which forces employees to take on uncomfortable positions, poor design of tools and machines; excessive heat increasing overall fatigue and excessive cold causing embrittlement of hands and more difficult gripping of tools [12] [13]; insufficient lighting, which forces employees to take up uncomfortable positions so that they can see the work well; high level of noise, which causes tension in the body [15] [16] [18]. Directional weight limits for both hand-lifted and carried loads, the maximum weight of a load for women is, under unfavorable conditions, up to 10 kg, over 50 years only 5 kg for a maximum of 1 hour for a change in standing position.

3. Method NIOSH lifting index
NIOSH Lifting Equation is a tool used by occupational health and safety professionals to assess the manual material handling risks associated with lifting and lowering tasks in the workplace. The NIOSH Lifting Equation is widely accepted as valid in the field of occupational ergonomics, providing occupational health and safety professionals an objective ergonomic risk assessment tool for manual material handling tasks. The NIOSH Lifting Equation is a great way to identify ergonomic opportunities and prioritize ergonomic improvement efforts, and it also provides an objective baseline from which we can document ergonomic improvements.

A lifting task is defined as the act of manually grasping an object with two hands, and vertically moving the object without mechanical assistance. The NIOSH Lifting Equation, see equation (1), considers several job task variables to determine safe lifting practices and guidelines.

\[ RWL = LC \times H \times V \times DM \times AM \times FM \times CM \]  
(1)

H = Horizontal location of the object relative to the body
V = Vertical location of the object relative to the floor
D = Distance the object is moved vertically
A = Asymmetry angle or twisting requirement
F = Frequency and duration of lifting activity
C = Coupling or quality of the workers grip on the object

The NIOSH Lifting Equation always uses a load constant (LC) of 23 kg, which represents the maximum recommended load weight to be lifted under ideal conditions. From that starting point, the equation uses several task variables expressed as coefficients or multipliers that serve to decrease the load constant and calculate the RWL for that lifting task.

The primary product of the NIOSH equation is the Recommended Weight Limit (RWL), see equation (2), which defines the maximum acceptable weight (load) that nearly all healthy employees could lift over the course of an 8-hour shift without increasing the risk of musculoskeletal disorders (MSD) to the lower back. In addition, a Lifting Index (LI) is calculated to provide a relative estimate of the level of physical stress and MSD risk associated with the manual lifting tasks evaluated.

\[ LI = \frac{Load \ Weight}{RWL} \]  
(2)

Table 1. Lifting Index (LI).

| LI < 1 | LI > 1 | LI > 3 |
|--------|--------|--------|
| nominal risk to healthy employees | high risk for some part of the population | the risk of damage to the musculoskeletal system increases |
A Lifting Index value of 1.0 or less indicates a nominal risk to healthy employees, as stated in the table 1. A Lifting Index greater than 1.0 denotes that the task is high risk for some fraction of the population. As the LI increases, the level of injury risk increases correspondingly. Therefore, the goal is to design all lifting jobs to accomplish the LI of 1.0 or less [14]. Material handling tasks should be designed to minimize the weight, range of motion and frequency of the activity, and using the NIOSH equation allows getting closer to optimum from the beginning.

4. Application of the ergonomic evaluation method in the workplace

4.1 Workplace and problem description

The assembly workplace of the heat exchanger was analyzed due to the manipulation with the weight range of individual pre-manipulated load parts from the lowest weight of 0.38 kg to the maximum weight of 16.6 kg.

| Table 2. Input data for NIOSH ergonomics analysis in the Tecnomatix Jack software. |
|-----------------------------------------------|-----------------------------------------------|
| Value | Input variable |
| HM | 0.45 | Horizontal location of the object relative to the body [cm] |
| VM | 0.9 | Vertical location of the object relative to the floor [cm] |
| DM | 0.99 | Distance the object is moved vertically [cm] |
| AM | 0.86 | Asymmetry angle or twisting requirement [deg] |
| FM | 0.74 | Frequency and duration of lifting activity [-] |
| CM | 1.0 | Coupling or quality of the workers grip on the object [optimal] |
| RT | 3.0 | Recovery time [hrs] |
| T | 7.5 | Working shift [hrs] |

Figure 1. Jack NIOSH: Editing input parameters.
A total of 9 plates for 1 reference type product are handled by the worker when assembling the heat exchanger while working on the workbench, and he must pay attention to the folding of the individual parts during handling, as they contain soft non-volatile parts that can be damaged by careless handling. When entering input data in the software Tecnomatix Jack, as in the figure 1, in addition to the weight of the load, we also need to know the working position of the worker, the frequency and duration of work operations, the rest time and the method or complexity of manual handling. Input parameters values are also listed in the table 2. For the reference calculation, we calculated the average height of a man at a selected workplace with values of 175.49 cm and a weight of 75.69 kg.

4.2 Assessment by NIOSH Lifting index method

The job position was modelled in the Tecnomatix Jack software, where the ergonomic risk when working with loads was evaluated by applying the NIOSH method.

By defining the necessary input data in accordance to the NIOSH methodology, an ergonomic risk analysis can be performed, thus obtaining a result in the form of a risk indicator, the so-called Lifting index - LI, which is the ratio between the actual weight of the lifted load and the recommended weight limit (RWL), see figure 2. From the point of view of the NIOSH method, if LI > 1, it means an increased risk of back pain in a certain fraction of the working population, therefore the goal should be to work with LI less than one.

The results from NIOSH ergonomic risk analysis can be concluded, that the load is greater than recommended limit for this task. Some healthy workers would find this job physically stressful. The following modifications are suggested:

- Bring the load closer to the worker.
- Reduce the lifting frequency rate and / or provide larger recover periods.
- Use industrial manipulators.
- Use particular exoskeletons.

5. Future experiment with exoskeleton application

Ergonomic load measurement can be applied at any workplace, in various work activities. Multi-sensor monitoring devices can be used for a variety of purposes, but vary widely depending on the actual sensor/system package configuration, availability, and user acceptance. Multisensory monitoring systems may be used in:
observation,
• interventions and randomized controlled trials to examine the effectiveness of the intervention or treatment,
• studies performing association analysis between exposures and outputs,
• as description of temporary patterns of physical activity intensity during the day.

At the same time, the platform can be used for workplace analysis not only in the laboratory, but also in industrial environments, research based on task analysis using wireless type-robust sensors (IMU / Motion, EMG, ECG, respiration, temperature, force, etc.). Our expectations consider improving the working conditions and comfort of employees, monitoring their health, safety and performance potential, and minimizing psychosocial risks.

In the figure 3, the employee wears chair exoskeleton and his motion activity is captured by camera, Captiv motion sensing system and smartwatch monitoring system Actigraph. The worker performs repetitive work assembling synchronous units in a gearbox. To reduce the load, the employee used a passive exoskeleton - a chair, which is designed to support the lower limbs.

The experiment can be carried out using protective aids, such as exoskeletons, where it is possible to determine the suitability of its use in a particular work activity and the duration and frequency of its application to workers. However, it is appropriate to apply the experiment without the use of exoskeletons, in order to identify the risk of damage to the musculoskeletal system. Both scenarios, with exoskeleton and without exoskeleton shall be tested and evaluated obtaining utmost accurate data by mentioned measurement systems developed and used by experts worldwide.

Used measuring systems:
  a) CAPTIV (motion analysis also includes a goniometer for measuring the position / angles of the limbs, EMG - muscle strength using 2 electrodes),
  b) Actigraph smart watch (ECG, metabolic expenditure, number of steps).

6. Conclusion
Considering increasing cases of back disorders in European Union among working population in the industry, especially in automotive industry working at production lines and assembly workplaces, based on European Risk Observatory Report, edited by European Agency for Safety and Health at Work, our research approach was focused on assessment of ergonomic risk of lower back. The presented case study was performed at heat exchanger assembly workplace in automotive industry. The specific workplace was selected due to the high values of hand manipulated weight, unacceptable working positions within object manipulation, frequency of work activity. Ergonomic risk analysis was performed using method NIOSH, which is suitable for manipulation activities with a higher load, considering the impact on a lower back. The real situation for the reference product was modelled in
the Tecnomatix Jack software. The NIOSH assessment results in Cumulative Lifting Index 1.291 confirmed the ergonomic risk, which is significant based on NIOSH method when the Lifting index exceeds the value 1. When value of Lifting index exceeds 1, the relevant measures has to be done, as work process / machine has to be changed, the load can be brought closer to the worker, the lifting frequency rate can be reduced, provided larger recover periods, suggested using of industrial manipulators, or particular exoskeletons.

Thus, further ergonomic studies are required in this case, considering optional process rework with using the exoskeletons for back support, which are suitable for weight manipulation as i.e. logistics operations. Another option can be using industrial manipulators. With the use of the exoskeleton to support the back, we assume a reduction in LI, which will be the subject of evaluation through the Captiv motion measurement system. We will also focus on measuring muscle strength with EMG (Electromyography) method. An additional measurement is the measurement of ECG and metabolic energy expenditure during work performed by the Actigraph system.

People in the work environment interact with various work equipment and technical equipment (computers, production machines, handling and transport equipment, etc.), so it is important that the work environment is adapted to eliminate the negative effects on health, motivation and productivity at work [4] [17]. The use of exoskeletons has the potential to benefit workers by augmenting a person’s strength, making him or her able to exert more force than normal, and reducing the strength exertions required of the person to perform a specific task.

The implementation of exoskeletons could be one of the solutions to increase human capacity and at the same time to reduce the large number of damage to the musculoskeletal system during work activities in industry. Safety is essential for both commercial and legal acceptance of industrial exoskeletons.

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