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Evaluation of static loads for manual warehouse work using computer simulation – case study

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Abstract

This article presents an analysis of the static loads on the human body during selected manual unloading tasks carried out by warehouse workers in a logistics company. The aim of the presented analyses is to minimize static loads in the work process and thus make the employees' work more comfortable. A tool in the form of 3D SSPP software for ergonomic workload assessment was used to carry out static load analyses. For the two selected activities, the values of the developed forces of statically working muscles and the forces acting on the vertebrae of the spine were determined. For the values of static loads identified, based on the simulation of the 3D SSPP program, modifications in work posture and a change in the manner of performing the tested activities were devised. Moreover, the proposed reorganization of the tasks examined was verified by the reassessment of the static loads on the muscles using the 3D SSPP tool. The analyses carried out after the reorganization of work confirmed the reduction in static loads and the improvement in work comfort for the analyzed manual tasks.

Introduction

Advances in mechanization and the automation of production processes have resulted in the spread of monotypic movement work, most often involving a high load on the muscles of the fingers, hands, and forearms. Performing this type of motor operations is usually associated with forced positions of the body and resulting postural stress (Gembalska-Kwiecień & Ignac-Nowicka, 2014; Janiga, 2014).

Data from the European Union countries indicate the great importance of loads on the body, with a large proportion of time spent working in static positions under contemporary working conditions. The data show that over 30% of workplaces in these countries are associated with difficult body positions, over 40% with highly repetitive hand movements, and nearly 20% with the need to move loads. This assessment is based on the assumption that a given type of load lasts for at least half the working time (Janiga, 2014). The described types of load contribute to fatigue and a decrease in a worker's exercise capacity, as well as various irregularities in the functioning of the musculoskeletal system (Tanaka et al., 2014; Galar & Kumar, 2016; Teymourian, Seneviratne, & Galar, 2019). Local overload can lead to degenerative changes that lead to pain in the muscles and spine. They most often occur in the dorsal part of the torso, including the neck and shoulders, and the lumbosacral region. An important element of the associated pain syndromes are changes resulting from overloads and microtraumas of the vertebrae and inter-vertebral cartilage (Gembalska-Kwiecień & Ignac-Nowicka, 2014; Janiga, 2014).

Static-type effort is a very important component of the overall workload. It consists in performing work when no limb or torso movement is observed, and the muscles remain tense and can counteract the force of gravity, e.g., holding a tool in a raised hand.

Static effort does not have a proportional rate of oxygen consumption and energy expenditure in relation to its severity, but it causes:

- severe fatigue;
- impairment of purposeful movements;
- negative impact on organs and systems responsible for the balance of the body;
- inhibition of the nerve centers that regulate circulation, respiration, and other activities (Konarska, Liu & Kurkus-Rozowska, 2002; Ignac-Nowicka, 2017).

An important feature of static operation is low energy consumption. Despite the low energy demand, the conditions for the formation of an oxygen debt and an increase in the importance of anaerobic changes are created in a statically working muscle. This results in the previously mentioned consequences, such as a feeling of discomfort and muscle weakness corresponding to fatigue (Ignac-Nowicka & Gembalska-Kwiecień, 2008; Ignac-Nowicka, 2012; Janiga, 2014). Under such conditions, workloads result in disturbances to the smooth performance of an employee's task. This may disrupt the production process in which the employee participates (Bernard et al., 2017; Teymourian, Seneviratne & Galar, 2017). Many such situations can be observed in warehouses, where manual unloading is dominant (Kabiesz & Bartnicka, 2018). Observation of warehouses and analysis of the discomfort reported by employees prompted the author to carry out a broader and detailed analysis of unloading tasks performed manually in order to optimize them and increase the comfort of performing selected tasks. Many cases of back and limb pain during manual unloading were reported in the analyzed enterprise. As the assessment of work or task ergonomics leads through the phases of prediction, recognition, and evaluation to corrective action, the static loads occurring during work (Stack, Ostrom, & Wilhelmsen, 2016) were analyzed, and a research tool was selected (Winkler, 2005; Ben-Daya, Kumar, & Murthy, 2016; Teymourian et al., 2021; University of Michigan software, 2022).

The problem of unnecessary static loads while performing tasks, especially physical ones, raised in this article, is a multilayered issue, affecting not only employees' health, but also work efficiency and company costs, which are concerns of employers. A company's losses can be twofold, not only caused by lowered work performance, but also long-term because of the health issues of qualified staff. With the use of a static loads simulating tool, effective measurement possibilities for the optimization of work procedures can be implemented. Such solutions can enhance both work performance and comfort by lowering static loads, as will be presented.

The research tool used

The methodology of technical design, and in particular computer-aided design, is aimed at achieving the best technical parameters to achieve the desired object. This often leads to solutions in which the relationship between workers and the equipment employed is disturbed. The use of computer aided design has become common, where the design features of the created technology are written as three-dimensional geometric models. The forms of notation used make computer simulations closer to real objects to an increasing extent. The equipment employed together with the people for whom it is intended create, in turn, increasingly complex anthropotechnical systems. Due to the use of models of both technological objects and human anthropometric features, it has become possible to create a virtual human environment in which the relationships connecting people with their work environment are mapped (Winkler, 2005; Plinta, 2010; Zywert & Czernecka, 2011; Gembalska-Kwiecień, 2018).

The spatial models of the equipment employed are created with the methods of geometric modeling available in many design applications. These models fill the virtual workspace. Human presence in the work environment is considered by modeling the anthropometric features of the human body (Galar & Kumar, 2016; Bernard et al., 2018). Currently, biomechanical models are used to determine and analyze the load states of the musculoskeletal system (Maurice et al., 2019; Kabiesz & Bartnicka, 2020). They are used to assess the loads caused by:

- the weight of body segments;
- loads lifted or shifted;
- human forces during technical operations (Plinta, 2010; Zywert & Czernecka, 2011).

A dummy biomechanical model is particularly useful in the process of studying the effects of negative interactions in the anthropotechnic system. These models were based on the principle of operation of the ergonomic design tool – 3DSSPP version 7.0.6. This program is a graphical representation of kinematic chains, with a particular emphasis on the analysis of static loads in the human musculoskeletal system (Teymourian et al., 2021; University of Michigan software, 2022). The 3D SSPP software was provided by the University of Michigan Office of Technology Transfer. It enables the simulation of work in a three-dimensional space, which includes data on posture, strength parameters, and male/female anthropometry (Maurice et al., 2019; Gomes et al., 2021; Vianello et al., 2022). The body position is selected by determining the values of the joint angles and the distance from the ground, or by shifting the anthropometric points of the manikin. The analyst can study the twists and bends of the torso and make entries about the strength of the hand. The analysis is supported by the automatic posture generation function and three-dimensional human graphic illustrations. In this way, the positions taken during the work are modeled, and the forces acting on the body are determined. The 3D SSPP software can assist the analyst in evaluating proposed designs and redesigning the workplace before actually building or rebuilding the workplace or task. The reporting functions implemented in the 3D SSPP program indicate the minimum possibilities of the joints assuming a given position, the amount of pressure on the L4/L5 vertebrae of the spine, the location of the center of gravity, moments and forces acting on the body, and the value of the maximum muscle contraction force expressed as a percentage (MVC – maximum voluntary contraction). After entering the data, the program generates three reports: loads, 3D analyses of the lower back, and a general report (University of Michigan software, 2022).

Workstation and activities selected for analysis

Modern warehouse logistics services currently include transport to and from the warehouse, consolidation (combining small shipments), deconsolidation, order picking, packing, repacking, securing, foiling, labeling, preparing promotional sets, adding instructions, warnings, and marketing gadgets, and distribution to the final recipient. The analyses performed in this research were carried out using a packer's workstation in the warehouse logistics services sector as an example. The most important tasks of the packer included:

- packaging of products,
- repackaging for the marketing needs of retail chains,
- labeling and kit making.

In the processes related to the abovementioned tasks, a human worker is indispensable due to the need for quick changes in the subject of work, as well as the required precision. The standing position of work, which forces the worker to tilt, as well as the manual handling of objects, causes static tension of the muscles. These loads are the greater the longer a person stays in a certain body position. Maintaining it in a long-term manner requires additional tension, leading to severe fatigue in the long term (Teymourian et al., 2021). At the analyzed workstation, the discomfort associated with the work performed had become a factor causing low quality of service, high employee turnover, and an above-average number of sick leaves due to ailments of the workers' musculoskeletal systems. Despite the work of a warehouse operative being strictly related to the lifting and carrying of loads, increased use of the upper limbs, and performing repetitive movements (repetitive work, i.e., monotypic movements), an attempt was made to select a number of critical positions that had the greatest impact on the overall comfort of work at the workstation.

After analyzing the work process of the warehouse operative, it can be concluded that the most common body positions taken during work are sitting, standing, and tilted standing postures. Activities are usually performed under the load caused by the weight of the lifted articles, as well as that from unusual twists of the body. The percentage share of the identified attitudes during warehouse operation is shown in Figure 1.

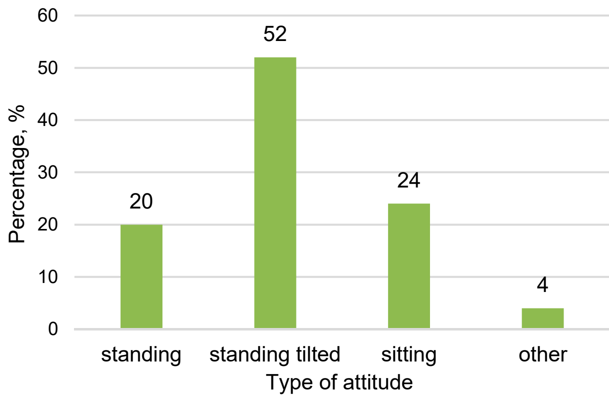

Figure 1. Occurrence of attitudes during the work of a warehouse operative

Overall physical effort is assessed in the sum of static load, energy expenditure, and motor monotypicity (Ignac-Nowicka & Gembalska-Kwiecień, 2008; Ignac-Nowicka, 2017). Regardless of the method of organizing and managing the work of the packer, it is not possible to eliminate the repetition of movements due to the characteristics of the workstation and the movements necessary to perform activities determined by daily norms. The analyses carried out below were performed to introduce improvements in the workplace in the form of the identification and elimination of excessive strain on the employee's body that could lead to fatigue.

Assessment of static loads using the 3D SSPP tool

The most common positions adopted by employees during warehouse work are the following postures: standing in a tilted position, which are characterized by increased energy expenditure, and a sitting posture. In these postures, work is usually carried out under a load caused by the weight of the lifted objects, as well as that caused by the usual twists of the body. More than half of the total working time involves a position where the muscles of the back and spine must be constantly tense to keep the head tilted past the base of the feet.

At the analyzed packer's workstation, the occurring static loads on muscles increased along with the increase in the weight and size of the packaging units handled. The necessity to transport them by hand, even over short distances, caused significant daily discomfort. During the pallet unloading operation, an employee lifted packages weighing 9 kg. The analysis of the load simulation was performed for a male employee with a height of 1.75 m and a weight of 84 kg, which corresponded to the 50th percentile group according to the anthropometric atlas (Nowak, 2000).

Load analysis for pallet unloading activities

When the packages were lifted from a pallet, an inclined standing position was assumed in the process of unloading. The worker gradually unloaded the pallet, assuming an ever-lower body position. Due to the low lifting height (about 12 cm above the ground), in the final phase of the activity the worker slightly bent their legs, bending their back at the same time and pulling their shoulder blades and arms forward to grasp the object. Placing many boxes on a pallet often effectively prevented the worker from conveniently gripping the item from underneath. Figure 2 shows the repeatedly observed, incorrect type of object grip used by employees, which put additional strain on the wrists. Figure 2 also contains two 3D SSPP simulation reports generated for this activity.

After analyzing the results of reports generated by the 3D SSPP program for the described activity, significant values of the loads on individual parts of the body were found. In particular, high forces were visible: the total compressive force F1 = 3778 N on

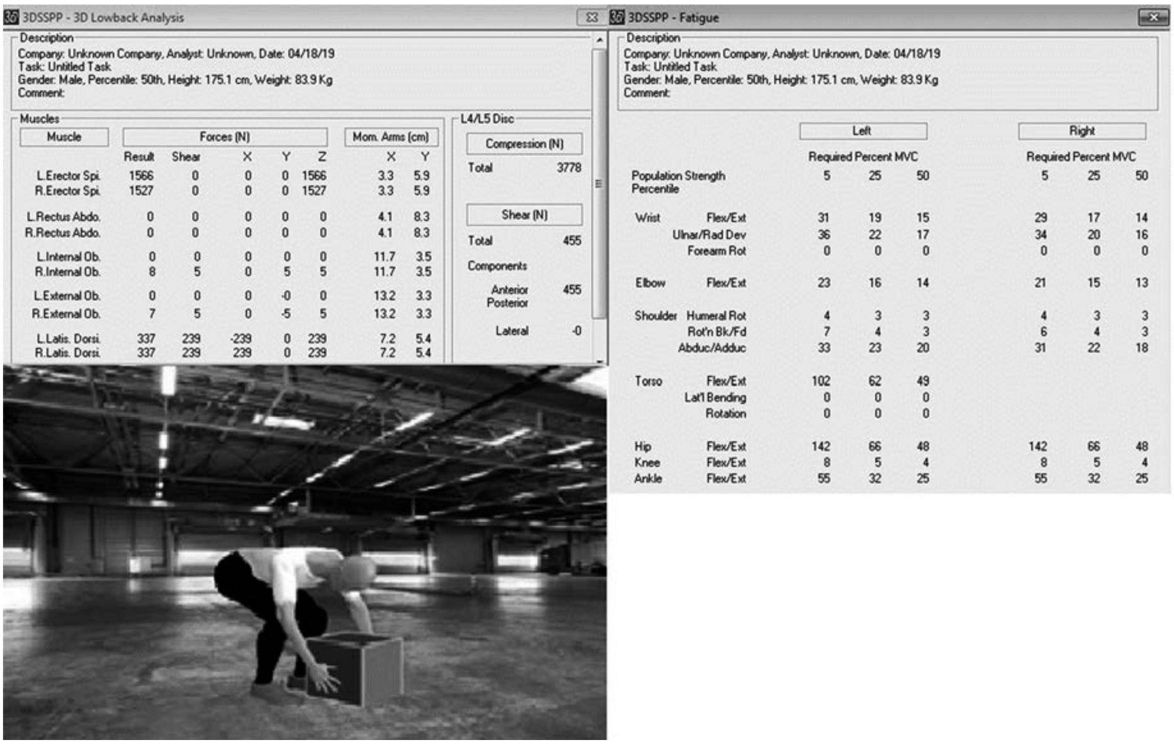

Figure 2. Screenshots of simulation of the loads for inclined standing posture during manual pallet unloading – 3D SSPP reports

the L4 and L5 vertebrae of the spine and the shear force on the L4 and L5 vertebrae with a value F2 = 455 N, mainly in the front plane (the table on the left side of Figure 2). Increased loads resulted to a large extent from the tilt of the torso, which introduced an element forcing a change in the position of the body's center of gravity, and this caused additional difficulties in maintaining balance during the analyzed activity. In the described case, attention is also drawn to the use by the employee of the contraction force of the iliopsoas muscles (MVC = 48%), the contraction force of the torso muscles (MVC = 49%), and muscle force at the level of the ankles (MVC = 25%). On the other hand, the load on the muscles of the upper limbs was less than 20% of the maximum strength of the worker's muscle tension (the table on the right side of Figure 2).

Load analysis for manual transport of packages

The employee, after picking up the carton from the pallet, took it to the workstation. In this phase of the work process, it was observed that the necessity to manually transport the package required a standing-type position in motion. Movement in this position was not forced or restrained in any way and was based on holding and carrying. The back was straight, and the arms kept as close to the torso as possible, but a load of 9 kg, carried over about 15 m, contributed to general fatigue due to the constant tension of the muscles of the shoulders, forearms, and lower back. In addition, there was a risk of dropping the object on the feet.

The 3D SSPP program load simulation report for manual transport activities is shown in Figure 3. For a weight of 9 kg, the L4 and L5 vertebrae load value obtained in the simulation for the standing-type stance in motion was F1 = 1781 N, while the shear force was F2 = 172 N. In addition, during manual transport, the following loads on the wrists could be detected: left = 33% of the force of maximum contraction, right = 41% of the force of maximum contraction (in the plane of natural wrist flexion). A significant load was also visible in the torso when twisting around the body axis, amounting to MVC = 69% for an employee in the 50th percentile group. The ankle load here reached a significant value of MVC = 32% for the right ankle (the table on the right in Figure 3), but this was a temporary load associated with shifting the weight alternately to individual limbs while walking.

Corrective actions for selected activities

To reduce the static load for the selected activities at the packer's station in the warehouse, changes were made to the position of the body during

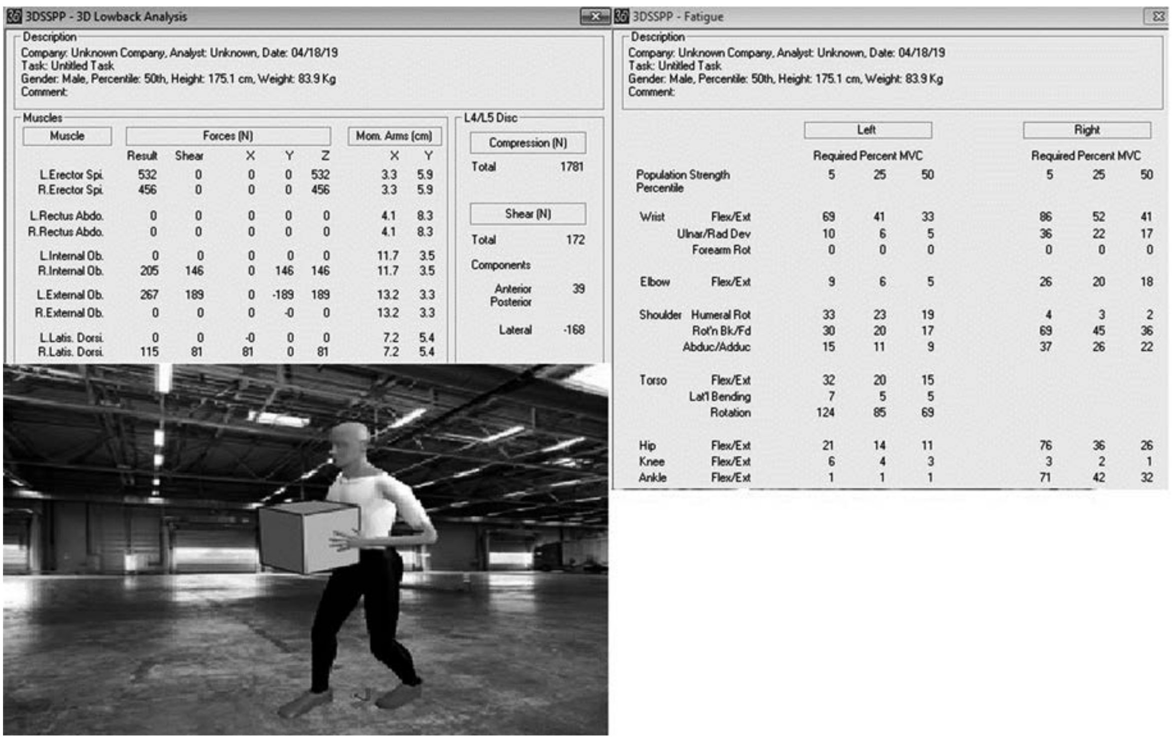

Figure 3. Screenshots of simulation of the loads for standing posture during manual transport of package – 3D SSPP reports

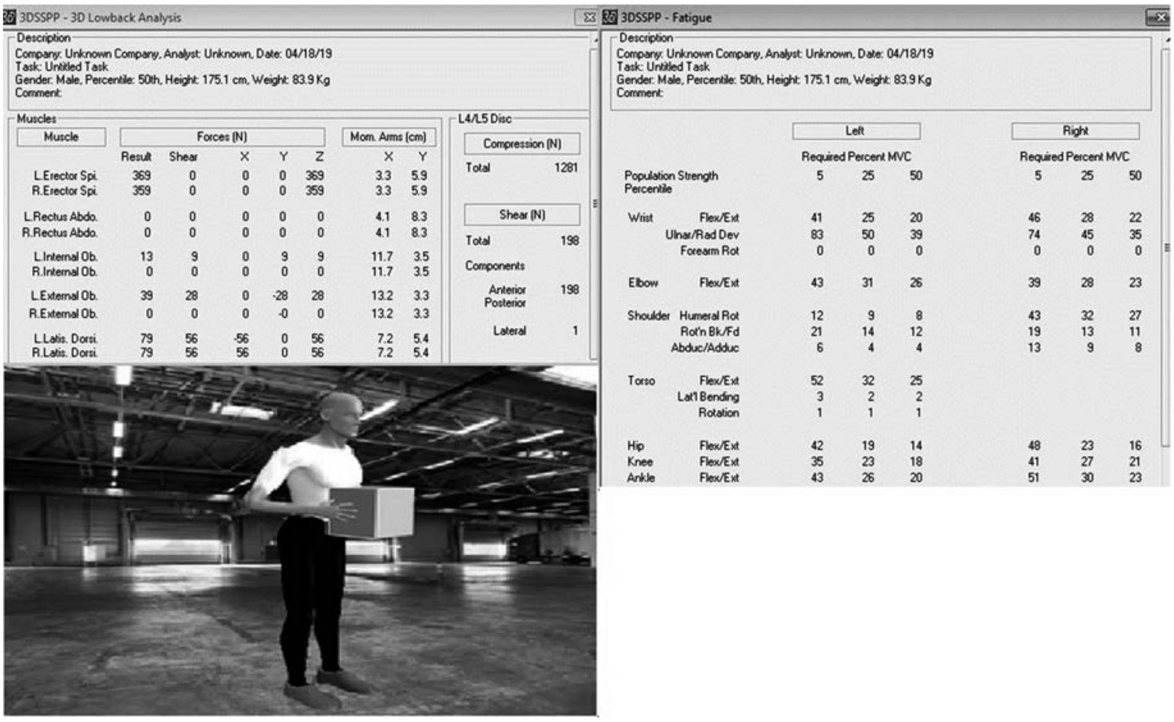

Figure 4. Screenshots of simulation for loads on the corrected standing posture during pallet unloading – 3D SSPP reports

operation, introducing improvements in the form of auxiliary devices. For pallet unloading, i.e., lifting packages from about 12 cm above the ground, it was proposed to use a lifting platform to raise the position of the pallet as it was unloaded. The lift, which contains hydraulic cylinders, can be built into the floor structure and lift objects weighing up to 800 kg on a square platform adapted to the size of the pallets. The platform can also be used to load items onto a pallet. The device in the form of a platform will eliminate the need for the worker to bend over while unloading or loading.

For the modified working posture, i.e., an upright standing posture with a load of 9 kg, a simulation analysis was performed using the 3D SSPP program. The report with the picture of the employee is shown in Figure 4. The pressure force on the vertebrae L4 and L5 decreased almost three times and amounted to F1 = 1281 N, while the shear force now amounted to F2 = 198 N. After introducing an improvement in the form of a platform, the hip load was also reduced from MVC = 48% to MVC = 14%. The loads on the upper limbs were at a similar level as before the improvement.

For the activity of transporting the packages, it was proposed to use a roller conveyor along the route of manual transport. In addition to relieving the employee during work, this improvement also reduced the time needed to perform this activity. The worker delivers the packaging to the roller conveyor and pushes the object while in a semi-standing position. In this case, the loads obtained from the simulation with the 3D SSPP program were reduced (from the value of pressure on the vertebrae of the spine L4 and L5 F1 = 1781 N and F2 = 1071 N). The value of the shear force on the vertebrae of the L4 and L5 spine slightly increased due to the need to perform a slight twist of the torso in a semi-standing posture using a high seat. The reduction of loads after the improvement was also visible for the hips, knees, and ankles of the packer.

Conclusions

The analysis of static loads carried out in the study for activities used as examples, such as the manual unloading of pallets and the manual transport of packages by a warehouse packer, revealed significant values of static loads. By using a tool in the form of 3D SSPP software, significant static loads were demonstrated for the manual unloading of pallets in the area of the iliopsoas muscles, the torso, and at ankle level. Moreover, significant effects of compressive and shear forces were found, which overloaded the L4 and L5 vertebrae of the spine. On the other hand, for the manual transport of packages, static loads were detected in the area of the wrists and torso, even with slight twists around the axis of the body, along with compressive and shear forces that loaded the L4 and L5 vertebrae of the spine. The tool used for the analysis of static loads was also used to search for a modification of the posture and the manner of performing the task in order to reduce the detected loads. The proposed solutions for the two tested activities are characterized by a decrease in the value of the forces developed by an employee and a decrease in the value of loads on the vertebrae of the spine. These improvements resulted in increasing the worker's comfort when carrying out the tasks.

The performed reorganization of the workstation to reduce static loads for selected activities required the use of additional elements in the form of appropriate seats for the employee, additional work surfaces, or simple devices to improve work. To effectively rearrange the workplace and obtain lower values of static loads, it is necessary to analyze the tension of the muscles of the limbs and torso and the forces that affect the skeletal system of the spine. The appropriate 3D SSPP software used (using human anthropometric and biomechanical data) was an effective tool in:

- the assessment of the risk of overloads occurring in some specific activities,
- the optimization of working conditions characterized by static loads.

Application of 3D SSPP software:

- allowed for the precise determination of the values of forces developed by the employee with respect to static loads for selected activities,
- made it possible to modify the posture and the way of performing the task in such a way that a reduction in static load was achieved.

As a result, the analysis carried out using this tool and the introduction of additional elements to the packer's workstation resulted in an improvement in the form of increased work comfort and reduced time for performing certain operations.

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