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ADDED VALUE OF MOTION CAPTURE TECHNOLOGY FOR OCCUPATIONAL HEALTH AND SAFETY INNOVATIONS

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Abstract: *Ergonomic principles in production assembly and manufacturing operations have become an essential part of comprehensive health and safety innovations. We aim to provide new insights into occupational health and safety innovations and how they utilise biomechanical methods and cutting-edge motion capture technology by assessing movements at a workplace. The practical goal is to quantify a connection between work exposure and ergonomic risk measures to determine biomechanical risk factors of diseases or health-related disorders objectively. The target group consisted of 62 factory employees working in manufacturing (26 participants on 12 devices) or assembly areas (36 participants on 9 devices). Body posture, body parts position, movements, energy cost and workloads were assessed using an inertial motion capture (MC) system. MC technology accurately assesses the operator's movements. The proposed methodology could complement ergonomic procedures in the design of workstations, which is the added value of the motion capture technology for occupational health and safety innovations.*

Keywords: *computer technology, motion capture, risk assessment, ergonomics, mobility, musculoskeletal disorders.*

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INTRODUCTION

Occupational health and safety interventions using a great variety of technologies (like VR, AI and bots) are becoming more and more valid. They are being used by many manufacturing corporations to protect workers against accidents, minimising as well as eliminating monotony, repetitive tasks, and working with heavy loads (Zhang et al., 2021). Nonetheless, the European Agency for Safety and Health at Work (EU-OSHA), the International Labour Organisation, and the WHO have been calling for a reduction in the increasing number of occupational health problems and new psychosocial risks in recent years. According to ESENER-3[1], the most frequently identified risk factors are repetitive work, dealing with demanding customers, and lifting or moving heavy loads. Moreover, the results of research conducted and reported by EU-OSHA (2019) have shown that the physical, organisational, and psychosocial factors contribute to the development of many work-related health problems faced by workers. Currently, the rising problems pertain to work-related musculoskeletal disorders (WRMSDs). WRMSDs concern workers in all sectors and occupations. Not only do they have a negative effect, but they also lead to high costs for businesses and society in general. Of all workers with a work-related health problem in the EU, 60% identify WRMSDs as their most serious issue[2]. Various examples of WRMSDs are diagnosed among employees: upper limb, lower limb, and back WRMSDs. The most common types of WRMSDs reported by workers are backache and muscular pains in the shoulders, neck, and upper limbs; muscular pains in the lower limbs are reported less often. Bearing in mind the multifactorial nature of WRMSDs, it is crucial to skilfully plan and conduct health and safety (H&S) interventions. Firstly, they should be holistic, integrated, and based on preventive and protective measures (e.g., the provision of ergonomic equipment, encouragement of regular breaks for people in uncomfortable working positions, and rotation of tasks to reduce repetitive movements). At this point, it is worth paying attention to the growing role of using technology in this area.

Besides, a prolonged standing position with the trunk motionless for an extended period may increase intervertebral stress (Gallagher & Callaghan, 2015) as well as thoracic and lumbar intradiscal pressure (Liebsch & Wilke, 2021; Polga et al., 2004). Moreover, this posture has been associated with the idiopathic viscoelastic deformation of lumbar tissues (Solomonow et al., 2003). Alterations in spinal curves may also affect the development of lower back pain (Oakley et al., 2005; O'Sullivan et al., 2017), Measurement of the fluid pressure in the intradiscal cavity shows the level of pressure changes during different daily life or working postures . It has been revealed, standing posture (with inclined trunk) may produce relatively higher disk pressures (by around 50%) than a seated upright posture, attributing to the fact that the line of gravity for the upper body acts farther away from the instantaneous centre of rotation. Several other vital applications of biomechanical analysis may be named. The lifting guidelines suggested by the National Institute of Occupational Safety and Health (NIOSH) employ the biomechanical criteria of a maximum acceptable compressive loading on the vertebral unit in setting the maximum load that an individual can safely lift. This recommendation includes some physiological and biomechanical factors for evaluating loading of the human body grounded on the physical limitations as a result of the strength or posture of the body (Barim et al., 2019; Fox et al., 2019; Waters et al., 1993). These involve: the variability in size and shape of the human body, the variability in types and range of movements, the mass and shape of handling object, frequency of lifting (repetitive hand or arm movements increases both the dynamic joint loading and the metabolic energy cost), forward and upward reach (static loading, increased LBP risk), working at very high speed, carrying or moving heavy loads, control at the endpoint of the loading, asymmetry of lifting, coupling of the load, etc. Other safety guidelines are found in designing different types of equipment, tools, or workstations to utilise the midrange of motion of body segments optimally. Existing WRMDs databases have documented the maximum forces that can be applied at various limb positions and body postures. These databases may be used to manage or supervise the amount of work output depending on the worker's posture without inflicting any form of harmful musculoskeletal loading. For example, the maximal two-handed mass /weight that can be transported repetitively by a male in a standing position is 10 kg (for the low-risk category, OCRA Index of 1) or 20 kg (for the high-risk category, OCRA Index of 3) (EN 1005-5, ISO 11228-3) but also depends on the frequency of repetitions (from 0 to 15 lifts per minute according to ISO 11228-1). High forces are associated with lifting relatively heavy objects to high levels, while the weight of the handled objects is often the main predictor of high loads and musculoskeletal forces (Skals et al., 2021). Any job requiring an individual to perform such a task should be designed in conformity with this criterion for avoiding worker discomfort and the possibility of WRMDs or injury. Such databases are limited in population size and scope and need to be expanded to include the specific working population or movement tasks under consideration (Karwowski & Marras, 2003).

In addition, several studies have found a relationship between spinal curves and ventilatory responses. A systematic study comparing lumbopelvic kinematics in people with and without low back pain (LBP) revealed no difference from asymptomatic people concerning the angle of lumbar lordosis or the angle of the anterior tilt of the pelvis in a standing position. However, people did show differentiation in terms of the lumbar spine's range of motion in all directions, its velocity, and worsened proprioception during movement relocation (Laird et al., 2014). There is also strong evidence that the size of motor variability in a healthy subject affects the prognosis for contracting pain and fuels the idea in occupational health that movement variation decreases the risk of developing MSDs (Srinivasan & Mathiassen, 2012). If movements are repeated more similarly, it would be more likely that the same soft tissues receive large doses of exposure. Increased movement and posture variability would thus modify tissue loads from repetition to repetition, distribute stresses more equally among tissues, and thus reduce the cumulative load on any particular tissue (Srinivasan & Mathiassen, 2012). The idea that a significant motor variability may have a protective role in preventing chronic MSDs has been proposed by Mathiassen, Burdorf, et al. (2003); Mathiassen, Möller, et al. (2003) and supported by Côté (2012), Madeleine, Mathiassen, et al. (2008) and Madeleine, Voigt, et al.(2008). Some researchers also indicate a strong link between WRMSDs (mainly LBP) and the task or movement asymmetry (Beaucage-Gauvreau et al., 2019; Kim & Zhang, 2017; Mehta et al., 2014). Increases in nonsagittal plane movement (lateral or twist) will usually accompany more asymmetric loads since the weight is located away from the midline of the sagittal plane, causing the individual to twist and bend sideways.

Health and safety (H&S) interventions are divided into three categories, according to their goals: primary—identification of causes and their subsequent elimination or reduction; secondary—supporting employees' ability to cope with the existing overload, teaching them appropriate techniques and skills; tertiary—psychological or medical intervention when the impairment or disease is already appearing (De Angelis et al., 2020; Nielsen & Randall, 2015;

Sinclair et al., 2010). The first goal is achieved through interventions at the organisational level, where more general solutions are implemented. The other two are the interventions focused on improving an individual's functioning, and they are named individual-level interventions (Dalgren & Gard, 2013; Richardson & Rothstein, 2008; Schabracq et al., 2004). Interventions focused on improvements in human work in manufacturing processes are based mainly on ergonomics (Bhattacharya & McGlothlin, 2011), but they are also related to many scientific fields such as physiology, physiotherapy, biophysics, occupational psychology, and occupational health (Karimi et al., 2020; Skals et al., 2021; Taibi et al., 2021). In this study, we want to combine the knowledge from those fields to add the value of motion capture technology into an in-depth analysis of human work. This is why the goal of the present study is to assess workplace movements at machining or assembly workstations, to state protective measures (through observation), and to identify and evaluate risk factors of health-related events (analytic study). A high level of work exposure with a combination of extreme angle values, body part loads, asymmetry of movements, high velocity of arms or extremally low movement variability could pose additional, biomechanical risk factors in work-related musculoskeletal disorders. Which is why we could establish evidence-based recommendations to improve H&S procedures and implement tailored programmes to avoid musculoskeletal problems or impairments.

METHODS

Participants' Inclusion Criteria

All measurements were made in a workplace environment in a plant of an automotive multinational corporation (MNC).

All participants were full-time employees working on the same shift. The variation in job tenure was moderate (0.5–40 years, mean = 12.3). The research included 26 employees (41.9 ± 9.6 years of age, body mass: 79.9 ± 13.6 kg, height: 1.76 ± 0.07 m) working in manufacturing on 12 devices and 36 employees (35.5 ± 9.5 years of age, 69.2 ± 13.3 kg, 1.69 ± 0.10 m) working in assembly areas on nine devices. The inclusion criteria were a minimum experience age of six months at the workstation, maximum age of 60 years, and no history of pain concerning the musculoskeletal system that could influence the range or speed of movements. Manufacturing (MWE) and assembly (AWE) workstations are evaluated against work-related risk factors every three years. During the evaluations, the following "ergochecks" (preliminary mapping of potential risks in workplace environment) are performed: (1) the identification of high-risk factors using the company's tailored risk assessment checklist (2) repetitive movements evaluations (ISO 11228-3 norm and the OCRA method in the risk assessment), (3) carrying, pushing and pulling objects (ISO 11228-1 and ISO 11228-2 norms), (4) lifting loads one-handed (EN 1005-2 norm) and two-handed (NIOSH norm). The company uses internal norms for all factory units. Mainly, they refer to load evaluation of hand, arm and fingers. According to the company's Health and Safety management and quality auditors, the MWE and AWE workstations are of low risk (green zone according to OCRA Index), but still, from the workers perspective, the participants were exposed to risk factors associated with WRMSDs (Bernard, 1997), such as (A) repetitive tasks involving cyclical flexion, extension, abduction and rotation of joints, (B) static posture, with flexed, abducted and extended arms, (C) strenuous work during production cycles, (D) lifting movements, (E) awkward positions with non-neutral trunk postures, trunk flexion, rotation and torsion. The research project was approved by the company's H&S division and supported by the human resources department. The biomechanical procedure complied with the Declaration of Helsinki regarding human experimentation. The study was also approved by the Rector's Committee for Research Ethics of Wroclaw University of Economics and Business (case no. 33/2020). After receiving all relevant study information, the participants signed informed consent, including permission to publish the data anonymously.

Measurement Set-Up and Procedure

All parameters were registered using an MR3 myoMuscle Master Edition system (myoMOTION™, Noraxon, Scottsdale, AZ, USA). The myoMOTION system consists of a set of 16 inertial motion units (IMUs) using inertial sensor technology. Based on fusion algorithms, the information from an IMU sensor (3D accelerometer, gyroscope, and magnetometer) is transformed to measure the 3D rotation angles (yaw-pitch-roll, also called navigation angles) of each sensor in absolute space. The inertial sensors were located on the body of the study employee to record the accelerations according to the myoMotion protocol described in the instruction manual. Previous research has checked and demonstrated the scientific validity and high accuracy of the IMU system in angle determination (±0.4 deg. for static and ±1.2 deg for dynamic analysis) (Bańkosz & Winiarski, 2021; Teufl et al., 2019). It is alleged that inertial motion capture technology is low cost and more potable than markerless optical technology, but the system's accuracy must be assured (Karatsidis et al., 2016; Yunus et al., 2021).

The research strictly followed the International Society of Biomechanics' recommendations on definitions of joint coordinate systems for reporting human joint motion and intersegmental forces and moments during human motion (Derrick et al., 2020; Wu et al., 2002, 2005; Wu & Cavanagh, 1995). Primarily, the inertial motion capture system employed a 16-segmental biomechanical model of the human body, Euler angles for determining the position and orientation of the segments in 3D measurement space, and the medical angles for describing the 3D movement after decomposing into three orthogonal planes of motion. All registrations were carried out in the manufacturing or assembly area of the company. Special care was taken during the acquisition to avoid sources of bias and confounding by eliminating nonworking movements or actions (e.g., stuck components, unplanned breaks, reaching for a bottle of water). No magnetic field interference or cross-talk artefacts from operating equipment were noticed as affecting the recording result.

IMU sensors were attached with elastic straps and self-adhesive tape so that the sensor's y-coordinate corresponded to the frontal horizontal axis and the z-coordinate to the sagittal horizontal axis of the body part (Figure 1). The sensors were placed according to the myoMotion protocol described in the manual. At the beginning of the measurement, each participant was checked, and the system calibrated according to the factory recommendations. The maximal sampling rate for a given sensor was 100 Hz per sensor for the whole 16-sensor set. We used system-build fusion algorithms and Kalman filtering (digital bandpass FIR filter). This approach allowed direct access to all unprocessed IMU sensor data for further computations.

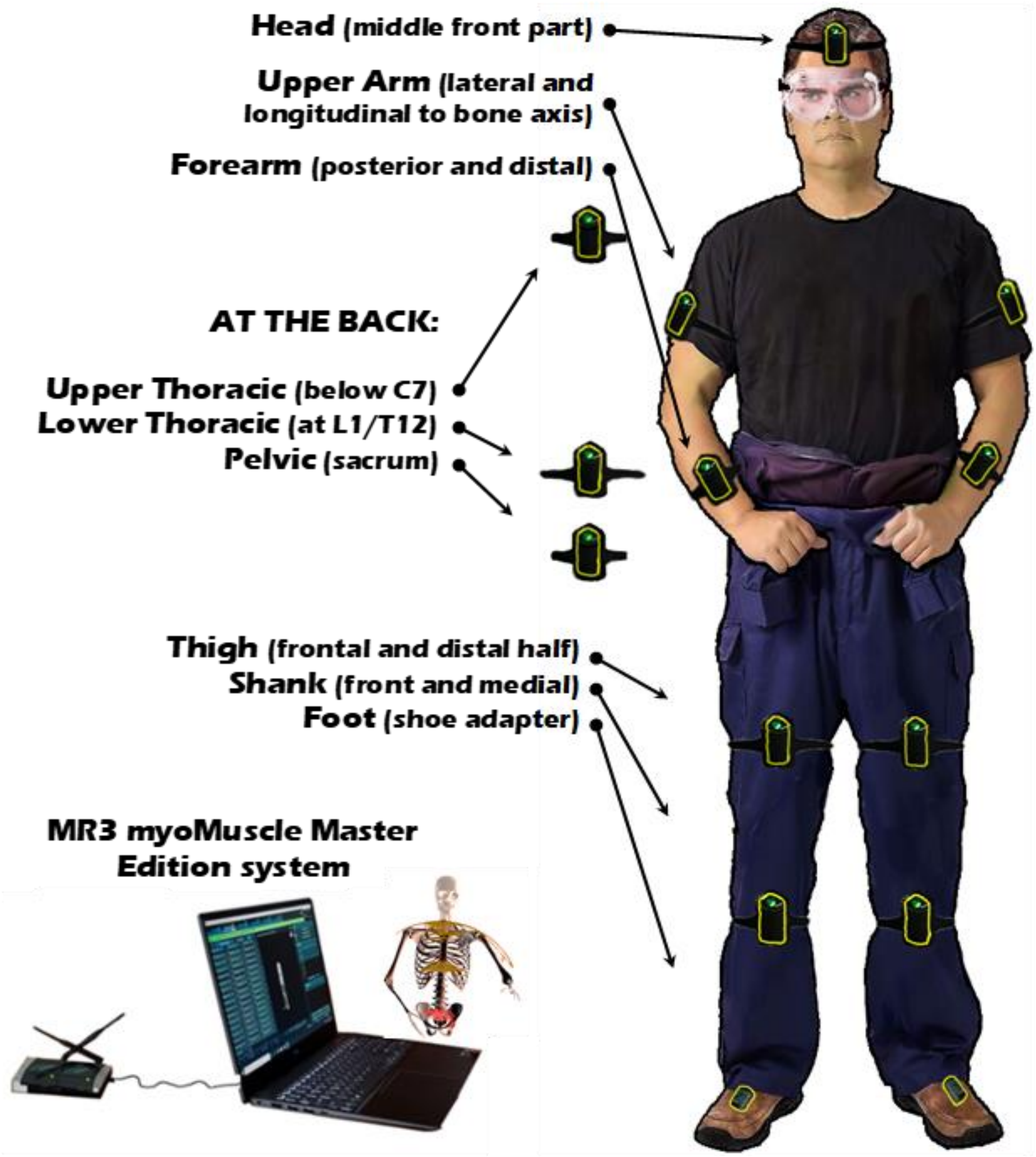

Figure 1. The measurement set-up with the computer workstation and locations of the sensors on the worker's body.

The standardised machining tasks involved (Figure 2): picking up four pieces at a time (three pieces in one hand and one piece in the other) from a metal container, clearing metal chips from the clamping base, attaching the pieces to the clamping device, starting the deburring process, placing the pieces in the engraving machine, starting the marking (engraving) cycle, visual inspection of the correctness of the operations carried out and, finally, placing the pieces on the hanger. Handling and operating the pieces at the machine was done single-handedly; picking up and moving on to the subsequent process was done two-handedly.

The weight of the handled component was about 520 g before the operation and 380 g after the operation.

The standardised assembly tasks (assembling the spring-piston unit) involved the following (Figure 2): picking up the spring from the spring pack container (with left hand) and the piston from the piston box (right hand), placing the spring pack vertically in the centring sleeve, and the piston on the spring pack, visual inspection of the correctness of the operations carried out and, finally, moving the spring-piston unit towards the next assembly slot. The weights of the assembled components were from around 100 to 400 g.

The repetitive tasks of all the workers were monitored during a 30 min observation period by an experienced technician utilising the same procedure.

Figure 2. A sequence of production activities at the machining (above) and assembly workstation (below). [Used with permission]

The production company employed ergonomic standards for studied workstations. Mainly, the working process is assessed at least every 3 years ("ergochecks") according to the following physical criteria: (1) identification of high-risk factors using tailored risk assessment checklist (2) repetitive movements (ISO 11228-3 norm and the OCRA method in the risk assessment), (3) carrying, pushing and pulling objects (ISO 11228-1 and ISO 11228-2 norm), (4) lifting loads one-handed (EN 1005-2 norm) and two-handed (NIOSH norm). Besides, the company uses internal norms for all factory units. Mainly, they refer to load evaluation of hand, arm and fingers. What is more, all measurements mentioned above were established in relation to EN and ISO norms, including the characteristics of participants' work, especially repetitive handling for high frequency (EN 1005-5 and ISO 11228-3), carrying, pushing and pulling objects and force limits (EN 1005-3 and ISO 11228-2 norms) lifting loads one-handed (EN

1005-2 norm ISO 11228-1). The references to ergonomics norms mentioned above were conducted throughout the measurement collection.

The data collected during the measurement were pre-processed by reviewing and discarding incorrectly recorded records (1 case). Each record was then verified against the workstation manual.

Data Processing

Workers' performance during professional activities (working operations) at the workstation was characterised comprehensively by different assessment levels and concerned, particularly, the measurement of mobility, (bio)energetics of movement, and inertial loads of involved body parts. Biomechanical and statistical calculations aimed to select the most relevant variables that are easy to interpret and could serve to clarify the research goals. All derived formulas conformed with classical mechanics and biomechanical standards on reporting human movement. Additionally, as mentioned above, the chosen variables correspond to general norms devoted to assessing risks for repetitive tasks, working postures, and force limits for machinery operations.

The production cycles of each employee were characterised by the number of cycles and the cycle time [in s]. The time at which the worker reached for the component was chosen as the beginning of the cycle.

The mobility of the employees for machining or assembly workstation employees were characterised separately by measuring angular displacements of the main body parts involved in the work, in particular: movement of the pelvis, lower back (loins), upper trunk (thorax), shoulder complex (links the upper arm to the axial skeleton at the thorax), upper arms, and arms connected by elbow joints. Following the International Society of Biomechanics' recommendations for the reporting of human joint motion (Bańkosz & Winiarski, 2020, 2021), the following angles (measured in degrees) were chosen for both sides and sampled every 0.01 per cent of cycle time (Figure 3), in particular:

- for the pelvis—pelvic tilt: forward (positive) or backward (negative) movement of the pelvis (with respect to the global coordinate system) in the sagittal plane; pelvic obliquity: upward (positive) or downward (negative) movement of the pelvis in the frontal plane; pelvic rotation: internal (positive) or external (negative) movement of the pelvis in the transversal plane
- for the lower trunk—lumbar flexion-extension: anterior (positive) or posterior (negative) movement of the loins in the sagittal plane; lumbar lateral flexion: movement of the loins to the left (upward) or right (downward) side in the frontal plane; lumbar internal-external rotation: internal (positive) or external (negative) movement of the loins in the transversal plane
- for the upper trunk: thoracic flexion-extension: anterior (positive) or posterior (negative) movement of the thorax in the sagittal plane; thoracic lateral flexion: movement of the thorax to the left or right side in the frontal plane; thoracic internal-external rotation: internal (positive) or external (negative) movement of the thorax relative to the global coordinate system in the transversal plane
- for the shoulders: left/right shoulder flexion-extension: anterior (positive or posterior (negative) movement of the humerus relative to the thorax in the sagittal plane; left/right

shoulder abduction-adduction: abduction (positive) or adduction (negative) of the humerus relative to the thorax in the frontal plane; left/right shoulder internal-external rotation: internal (positive) or external (negative) rotation of the humerus in the transversal plane

- for the elbows: left/right elbow flexion-extension: positive (flexion) or negative (hyperextension) movement of the forearm relative to the humerus along the transversal axis

The movement of hands with respect to forearms had to be excluded in the study due to the presence of protective gloves that would significantly interfere with the installation of the IMU sensor and could influence the production cycle. Similarly, the employees' standing posture determined that the analysis of the movement of the lower extremities has been omitted. The following parameters were chosen to characterise the mobility graphs: maximum value (Max), minimum value (Min), the median value of angular position (median) together with cycle variation characteristics—interquartile range (IQR, for skewed distributions) and coefficient of variation (CV = standard deviation/mean). Movements characterised by extremal (Min or Max) median angle values, asymmetry of movements (mainly excessive tilts from the neutral position or side differences) or extremally low or high movement variability characterised by the CV were considered as a potential risk symptom in work-related musculoskeletal disorders (WRMDs).

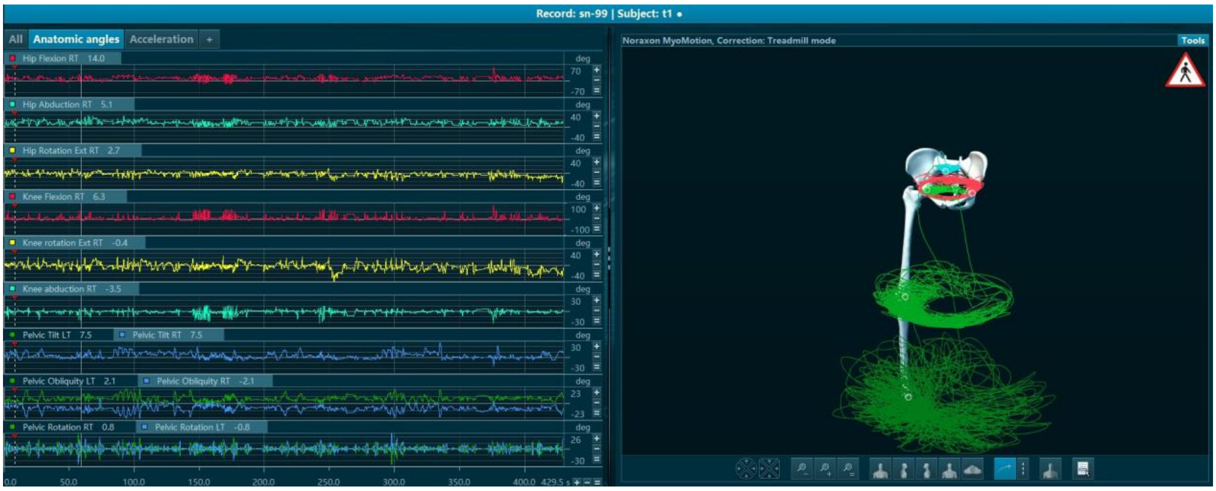

Figure 3. Angular values (temporal angular trajectories) characterising the movements of the tested joints.

The energetics of movements was characterised by the total mechanical energy (TME) expenditure and the average mechanical power (rate of change in TME). The total mechanical energy (TME) comprises of the instantaneous potential energy (PE) and instantaneous kinetic energy (KE) of the resultant centre of gravity (CoG) of the body, according to equation (Eq.1):

$$\begin{Bmatrix} PE(t) = M \cdot g \cdot h_{CoG}(t) \\ KE(t) = \frac{1}{2} \cdot M \cdot v_{CoG}^2(t) \end{Bmatrix}, \quad \text{(Eq. 1)}$$

where M is the total body mass [in kg], g = 9·81 [m·s^{-2}] is the gravitational constant, $h_{CoG}(t)$ is height of the CoG [in m], and v_{CoG} is resultant speed of CoG [in m·s^{-1}]. The velocity of the CoG was computed by integrating the triaxial information from the accelerometers (Figure 4).

For the calculation of instantaneous PE, only an increase in the height of the CoG (CoG amplitude) was considered so that the minimum values of PE and KE were equal to 0. The TME was the sum of total PE and total KE over the whole measurement period considered. Finally, the energy values were normalised against time to compare the values to tabulated data and expressed per minute of work, forming the average mechanical power [in joules per minute of work].

Similarly, parameters like Min, Max, Median, IQR and CV were chosen to characterise the energetics of movements. Extremal (Min or Max), median values, or extremally low/high energy cost variability were considered a potential risk symptom of WRMDs.

Figure 4. Acceleration values (3D signals from triaxial accelerometers).

At the last stage of data processing, the variables characterising *inertial loads of the body parts* were determined. In the case of linear movements, inertial loads were defined as the product of mass and resultant linear acceleration and in angular movements as the product of moment of inertia and angular acceleration, according to Eq. 2.

$$\begin{Bmatrix} Load_{linear} = M \cdot |\bar{a}| \\ Load_{angular} = I \cdot |\bar{\varepsilon}| \end{Bmatrix}, \qquad \text{(Eq. 2)}$$

where M is body mass [in kg], I is moment of inertia [in kg·m^2], $|\bar{a}|$ is the resultant linear acceleration [in m·s^{-2}], and $|\bar{\varepsilon}|$ is resultant angular acceleration [in rad·s^{-2}].

For this purpose, an estimation of the mass and length of each body segment was performed for each individual (Figure 5), using inertial coefficients according to (de Leva, 1996). Ultimately, characteristics of body parts involved the relative mass ratio (total weight * mass ratio), the relative position of the centre of mass on the long axis (segment length * length ratio) and the principal radii of inertia coefficients (de Leva, 1996; Derrick et al., 2020). The triaxial accelerations of the IMU sensors placed on different parts of the body (blue squares in Figure 1) were determined (in particular on the pelvis, lower back (lumbar) spine, upper (thoracic) spine, left/right upper arm, left/right forearm) and measured in one-thousandths (milli) of the earth's acceleration (mG).

Finally, the parameters Min, Max, median, IQR and CV were chosen to characterise the inertial loads of main body parts involved in work. Extremal (Min or Max), median values or extremally low / high variability in the inertial loads were considered as a potential risk symptom in WRMDs.

Figure 5. The three degree and 16 body parts model for the determination of segment mass and length.

Statistical Calculations

Statistical calculations were performed using Statistica 13.1 (TIBCO Software Inc.). The normality of the distribution of continuous variables (for each extracted variable in each test group) was tested by the Shapiro-Wilk test. Nonnormal variables were reported as median and ± interquartile range (± IQR). The IQR, also called the midspread, is a measure of statistical dispersion around the median, equal to the difference between upper and lower quartiles (IQR = Q3−Q1). The Mann-Whitney U test was used to assess the differences between machining (MWE) and assembly (AWE) workstation employees (with the $\alpha = 0.05$ level of significance) based on the normality test results. MWE and AWE workstations appear similar in terms of standing posture and work characteristics (common is the job rotation) but may significantly differ in activity, workload or energy cost. The statistical power was sufficient to detect the described differences. Especially for the extracted data, the partial η^2 effect size was found to be between 0.68 and 0.88. In addition to the median value, the Min, Max, and CV were averaged for all employees and devices. The descriptive analysis included repeatability analysis employing the Coefficient of Variation (CV). The following interpretation for the movement variability based on the CV was adopted: CV < 50% was considered as low variability/diversity (and high repeatability); 50% < CV < 100% as moderate variability; CV > 100% as high variability (and low repeatability).

RESULTS

Production Cycles

Descriptive analysis of production cycles, including the number of cycles and cycle time duration [in s] for both the machining workstation employees (MWE) and assembly workstation employees (AWE), is provided in Table 1.

Table 1. Descriptive Analysis of Production Cycles Characterised by the Median Value (Med) and Interquartile Range (± IQR), Min, Max, and Coefficient of Variation (CV) for Both Machining and Assembly Workstation Employees (MWE and AWE).

Variable	Machining workstation employees				Assembly workstation employees			
	Med ±IQR	Min	Max	CV (%)	Med ±IQR	Min	Max	CV (%)
Number of cycles [/]	5.8±2.3*	2	17	43.1*	18.1±5.2	15	38	33.3
Cycle time [s]	201.2±96.6*	28.4	375.2	53.0*	12.7±4.4	8.1	30.4	34.7

Note. * denotes changes statistically significant at $\alpha<0.05$

The work of those in the MWE group was characterised by a smaller number of production cycles (from 2–17; 5.8 on average) but a longer time of cycles (201.2 s). Those in the AWE group had more cycles (from 15–38; 18.1 on average), but it was compensated for by a shorter cycle time (12.7 s). The work on assembly positions was significantly more repetitive (less variable).

Mobility

Descriptive analysis of mobility characterising angular displacements of the main body parts involved in the work, for both the MWE and the AWE is presented in Table 2.

Table 2. Descriptive Analysis of Mobility. Joint Angles [in degrees] for the Movement of Different Body Parts Characterised by the Median Value (Med) and Interquartile Range (±IQR), Min, Max and Coefficient of Variation (CV) for Both Machining and Assembly Workstation Employees (MWE and AWE).

Body parts	Angle [deg]	Machining workstation employees				Assembly workstation employees			
		Med ±IQR	Min	Max	CV (%)	Med ±IQR	Min	Max	CV (%)
Pelvis	Pelvic tilt	1.9*±2.8	-8.0*	24.9*	211.5	0.1±2.9	-5.7	10.3	6.7
	Pelvic obliquity	-0.8±2.0	-13.6*	13.7*	30.5	-0.7±3.1	-6.9	6.5	264.0
	Pelvic rotation	-0.1±1.2	-21.1*	21.2*	250.3	0.0±3.0	-12.8	12.8	990.8
Loins	Lumbar flex-ext	5.7±6.1	-4.6*	29.3*	59.9	5.5±2.5	1.0	11.6	53.2
	Lumbar lateral flex	0.2±3.8	-10.6	12.2*	163.7	1.2±2.2	-3.1	6.2	58.2
	Lumbar rotation	1.4±5.5	13.7	17.2*	82.9	1.7±2.4	-4.1	6.7	37.4
Thorax	Thoracic flex-ext	1.3±3.1	-12.2	13.2*	67.4	1.3±2.6	-5.0	6.1	22.5
	Thoracic lateral flex	0.0±3.9	-11.3	13.7*	230.3	-0.7±2.1	-5.7	3.6	21.7
	Thoracic rotation	2.9*±6.7	-16.7	20.3*	97.7	-1.6±3.3	-8.6	5.7	17.8
Shoulder	LT Shoulder flexion	16.4±18.8	-20.3	71.5*	133.6	12.1±16.4	-10.8	55.4	169.5
	RT Shoulder flexion	23.5±19.4	-13.3*	77.0	90.8	18.3±13.2	-9.4	63.3	48.2
	LT Shoulder abduction	8.4±12.3	-30.3*	58.6	198.8	12.1±11.5	-7.1	44.9	124.1
	RT shoulder abduction	6.5*±7.6	-45.4*	66.1*	163.9	12.3±12.4	-11.1	47.9	502.5
	LT shoulder rotation	-43.9±16.3	-95.4*	3.2*	70.3	-39.1±12.3	-68.3	-8.7	34.4
	RT shoulder rotation	-50.8±16.5	-102.3*	0.2	36.1	-38.4±15.1	-70.8	-0.9	53.0
Elbow	LT Elbow flexion	32.3*±16.4	-14.2*	92.2	96.9	57.3±19.1	5.9	87.6	53.0
	RT Elbow flexion	33.1*±15.5	-14.9*	94.0	83.0	51.5±18.8	1.2	86.5	47.1

Note. * denotes changes statistically significant at $\alpha<0.05$

Movement of the pelvis, assessed in three movement planes, was characterised for both the MWE and AWE groups by a relatively symmetrical pattern (median angle values close to neutral position or Min/Max values evenly distributed), except pelvic tilt for the MWE, which was significantly tilted to the front by 1.9 deg. Movement of the pelvis for MWE was characterised by a statistically significant higher range (Max–Min) than for the AWE group. Variation in those movements was from low (for the fore-aft tilt of AWE and left-right obliquity of MWE) to high (pelvic tilt and rotation of MWE and pelvic obliquity of AWE) and even very high (for pelvic internal-external rotation of AWE).

The movement of the lower trunk (loins) was somewhat asymmetrical for both the MWE and AWE groups. On average, the loins were forwardly flexed (anteriorly tilted) by around 5.5 deg. from their neutral position (both groups). Besides, the range of these asymmetrical movements differentiated the two groups. The range of all movements for the MWE group was significantly higher than for the AWE group. The variability in these movements was relatively moderate except for side flexion (obliquity) for the MWE group, which was high.

A similar pattern was observed for the movements of the upper trunk (thorax). Movements, especially rotational, were asymmetrical. On average, the thorax was internally rotated by 2.9 deg. for MWE and externally rotated by 1.6 deg. for AWE. Similarly, the range of thorax movements was higher for the MWE than for the AWE group. There was moderate variability and repeatability of thoracic movements. Similarly, the thoracic lateral flexion for the MWE group was the most variable (and the least repetitive).

Movements of arms in the shoulder joint were assessed independently for the left and right sides in three planes of motion. The median angle values were far from the neutral (zero) values, which suggests they were persistently used throughout the whole working process. The median shoulder flexion value for the MWE group was higher than for the AWE group, both for the right and left sides, but the differences are insignificant mainly because of the high variation in these movements. What could also be seen is that the AWE group's upper arm was abducted more than that of the MWE group for both sides. Both groups had their shoulders externally rotated (more than 38 deg. for MWE and more than 44 deg. for AWE on both sides). Again, the range of movements was significantly higher for the MWE group with variation from moderate to very high, especially for the shoulder abduction angle.

The elbow joint was at 30 deg. of flexion for the MWE and 55 deg. of flexion for the AWE group throughout the whole observation period, ranging from 90 deg. for the AWE to 105 deg. for the MWE group. The differences were statistically significant. The repeatability of these movements was moderate—higher for the AWE than for the MWE group.

Energetics of Movements

The energetics of movements was characterised by the total mechanical energy (sum of instantaneous kinetic and potential energy) and the average mechanical power (rate of change in TME). The results of the calculations are presented in Table 3.

Table 3. Descriptive Analysis Of The Energetics Of Movements. Instantaneous Mechanical Energy And Total Mechanical Work During the 30 min Observation [in kJ] Characterised by the Median Value (Med) and Interquartile Range (±IQR), Min, Max and Coefficient of Variation (CV) for both Machining and Assembly Workstation Employees (MWE and AWE).

	Machining workstation employees			Assembly workstation employees		
Variable	**Med ±IQR**	**Max**	**CV (%)**	**Med ±IQR**	**Max**	**CV (%)**
Instant. Potential Energy [J]	786.7*±13.8	801.8*	15.0	613.6±12.7	618.6	12.4
Instant. Kinetic Energy [J]	0.1±0.3	12.2*	266.3	0.1±0.2	2.5	152.9
Total Mechanical Energy [kJ]	141.62±19.40	345.95*	87.9	110.42±18.10	211.31*	78.8
Average Power [J/min]	5634.3±557.8	6807.2	189.6	4394.1±19	5676.5	94.8

Note. * denotes changes statistically significant at $\alpha<0.05$

The instantaneous potential energy (PE) depended on an individual's mass and body height and was normalised to body length. Due to a larger amplitude of the CoG, the PE was also larger for MWE group by 170 J on average. The minimal value of the instantaneous PE and KE was equal to 0 and was omitted from the table. The KE was dependent on the speed of the CoG but had a low contribution to the total energy (compared to PE)—maximally only 12.2 J (for MWE) or 2.5 J (for AWE). There were almost no differences between the groups, which is why the total energy expenditure (during the 30 min of work) was 141.6 kJ (for MWE) and 110.4 kJ (for AWE) or 5634.3 J/min (for MWE) and 4394.1 J/min (for AWE) on average. The highest values of the average power (P) reached 6807.2 (for MWE) or 5676.5 (for AWE) and were statistically significant. The variance of the results was low (for the values of PE) and rather high or very high for the values of KE, TME, and P.

Inertial Loads of Body Parts

Descriptive analysis of mobility characterising inertial loads of different body parts involved in the work for both the MWE and AWE is presented in Table 4.

Table 4. Descriptive Analysis of the Inertial Loads of Main Body Parts Involved in Work Characterised by the Median Value (Med) and Interquartile Range (±IQR), Min, Max and Coefficient of Variation (CV) for Both Machining and Assembly Workstation Employees (MWE and AWE).

	Machining workstation employees			Assembly workstation employees		
Variable	**Med ±IQR**	**Max**	**CV (%)**	**Med ±IQR**	**Max**	**CV (%)**
Pelvis load [N]	14.7±13.3	79.0	92.8	10.2±7.3	75.1	72.9
Loins load [N]	15.1±10.3	69.3	83.9	11.0±7.6	66.3	71.0
Thorax load [N]	15.7±9.0	73.2	78.7	11.4±7.7	69.2	69.3
LT Upper arm load [N]	29.8±21.2	181.6*	91.9	27.2±19.7	135.8	86.1
RT Upper arm load [N]	34.5±14.9	173.0*	75.2	33.7±21.5	151.7	79.4
LT Forearm load [N]	39.5±16.7	193.3*	85.7	37.5±23.7	161.3	82.6
RT Forearm load [N]	40.7±28.3	284.6*	95.5	38.5±32.5	263.0	83.2

Note. * denotes changes statistically significant at $\alpha<0.05$

All inertial load values for each segment of the MWE group tended to be higher than for the AWE group, but the differences were statistically insignificant due to the high deviation in the results. The inertial load was based on the resultant acceleration of each segment. That is why the minimal value (0) was omitted from the table. The lowest values of inertial load were noticed for the lower body parts, owing to small acceleration. Although the mass of these segments is relatively high, the overall load is relatively low. The highest median values of inertial loads (40 N) were noticed for the MWE group's forearm movement (right side). However, some workers achieved values of up to 285 N due to high acceleration and deceleration periods in forearm movement. The variance of the results was moderate, ranging from 71% to 95%

DISCUSSION

According to the United States Bone and Joint Initiative (USBJI), the US national action network of the Global Alliance for Musculoskeletal Health, adults in the workplace reported nearly 364 million lost workdays due to different musculoskeletal conditions—more than any other chronic health condition (Lezin & Watkins-Castillo, 2018). Repetitive motions, such as twisting, pushing, lifting, pulling, prolonged sitting or standing, unhealthy posture, and vibrations, can cause or aggravate musculoskeletal disorders (Antwi-Afari et al., 2017; Lezin & Watkins-Castillo, 2018). Several ergonomic risk assessment methods have been developed to improve the prevention, diagnosis, or treatment of musculoskeletal conditions and identify risk factors to make measurable improvements in the work environment. Among these methods, observational methods based on objective measurement in the work environment are among many ergonomic assessment tools to evaluate ergonomic risk factors that have gained high recognition (Antwi-Afari et al., 2017; Nunes, 2009). Motion capture is a powerful tool used in many applications for human motion capture, ranging from the entertainment industry to medicine and sports.

The motion capture system in our study assessed the mobility of different movements and the energy cost and loads of different body parts at assembly or machining workstations. Briefly, the most startling findings were as follows: the asymmetrical and countermovement positioning of the pelvis with respect to the loins and whole trunk for AWE induces twists and stresses that could produce lumbar intradiscal pressure; the median angle values of the pelvis were far from neutral (zero) values, which suggests they are persistently used throughout the whole working process; the movements of the upper limbs and trunk were characterised on average by noticeably low angular velocities; the change in kinetic energy was relatively small; and the highest values of accelerations were registered with a strong predominance of right upper-limb movements. The accelerations of the pelvis, loins, and thorax were relatively small. The highest range of movement for the pelvis was noted for pelvic rotation (31 deg.). Pelvic movements were relatively symmetrical (~0 deg. with small intersubject deviation from the median). The highest range for the loins (lower trunk) was spotted for the flexion-extension movement in the sagittal plane (18 deg.) and lateral flexion in the frontal plane (19 deg.) with an asymmetrical pattern (median position around 2–5 with moderate intersubject deviation). The thorax (upper trunk) was used in all planes: in the sagittal plane with a range of 16 deg., in frontal with a range of 15 deg., and mainly in the transversal with a range of 22 deg., on average. The movements were reasonably symmetrical with moderate (for the thorax flexion-extension and lateral flexion) or high (for the rotation) variability. These findings imply a high risk of work-related problems in the pelvis and lower trunk due to asymmetrical positions and excessive rotation. However, the findings revealed relatively no risks for the thorax.

The typical, normative pelvis, loins, and thorax values are hardly used in the ergonomic assessment. The motion capture method gives a broader perspective on human performance analysis, work-related musculoskeletal disorders, and injuries assessment. Our study noted the highest dynamic range of movement in the shoulder and elbow joints (Table 2). The range for shoulder flexion-extension was around 75 deg., around 65 deg. for abduction-adduction, and from 75 to 82 deg. for rotation with a high predominance of right upper-limb movements. These ranges correspond to 36% (for shoulder abduction-adduction) or 55% (for shoulder rotation) of the normative range of movement (50 percentile) when compared to normative joint movement ranges for males and females aged 20-44 (Soucie et al., 2011; Stubbs et al., 1993). Also, the elbow flexion-extension was of the order of 90–95 deg., with a high predominance of the right. To be noted is the asymmetrical positioning of the pelvis with respect to loins for the AWE group. Pelvis and loins were rotated internally (with median position 1.7 ± 2.4 with min -4.1 to max 6.7 deg.) and thorax rotated externally (median -1.6 ± 3.3, min -8.6 to max 5.7 deg.). The difference was around 3.5–10.0 deg., on average. This compensation mechanism for prolonged asymmetric conditions could lead to low back pain. Furthermore, the median angle values were far from neutral (zero) values, which suggests they are persistently used throughout the whole working process. Both groups had their shoulders externally rotated (more than 38 deg. for MWE and more than 44 deg. for AWE on both sides) which is common in manipulative hand movements and power grasping tasks (Jafari et al., 2018). The variation in these movements, especially during flexion-extension and abduction-adduction on the left side, was high or very high, suggesting high upper-limb involvement. Additionally, the symmetry between sides often exceeded the assumed 10% level, which further indicates a possible risk of musculoskeletal overload.

Findings from this in-depth analysis suggest the need for a redesign of the workstation and production system. Regarding norms for manual handling tasks (Ciriello & Snook, 1999; SHOAF et al., 1997; Snook & Ciriello, 1991), both AWE and MWE hold an upper limb too long in an extended position, especially for shoulders and elbows. Most of the registered deviations from neutral (standing) position for the trunk fell into either Green or Yellow preferred Zones for angular measurements of range of motion (ROM) as defined by Chaffin et al., 2006 and Woodson et al., 1992 (adopted by Openshaw & Taylor, 2006). According to the trunk ROM limits upper bands for the second, Yellow Zone should not exceed 25 deg for back flexion, 10 deg for back extension, 10 deg for lateral bend or 25 deg for back rotation, which corresponds to the lumbar flexion-extension, lumbar lateral flexion or lumbar rotation in our study. Some of the MWE workers (with extremal ROM values of around 29 deg of lumbar flexion or 12 deg of lumbar lateral flexion) fell into the third, Red Zone posing a potential WRMSD risk factor. Findings from the motion capture system may be used both as a replacement and complement to standardised ergonomic assessment tool as RULA (Rapid Upper Limb Assessment).

Maintaining proper body posture and movement during work is essential! The human pelvis supports the abdomen's contents while also transferring weight from the spine to the lower limbs. The lower and upper joints work together to decrease the force transferred from the ground to the spine and upper extremities during movement. During working manoeuvres, the shoulder girdle structures are designed primarily for mobility, allowing both to move and position the upper limbs through a wide range of space and the greatest range of motion for any joint. In a systematic review by Swain et al. (2020), a consensus was established for the absence of an association between exposure to prolonged or occupational standing, sitting, bending, and twisting, awkward postures, and low back pain (LBP). The evidence was conflicting for the other physical exposures examined, including sagittal spine curvatures, prolonged or occupational standing, awkward postures, bending and twisting movements of the spine, components of heavy physical work, and whole-body vibration (Swain et al., 2020). When considering meta-analyses alone, consistent, significant, and positive associations were demonstrated between maintaining flexed and awkward postures and LBP (Griffith et al., 2012). Acute, nonspecific LBP, which is not attributable to a recognisable or known specific pathology, can lead to subacute or even chronic low back pain (Burton et al., 1995). The strategy for finding a cause of the nonspecific low back pain is problematic; it is crucial to understand the functional lumbar spinal unit. Several methods have been developed to diagnose WRMSDs. Most of them are based on job surveys and surveillance techniques (Kroemer et al., 2018; Marras & Karwowski, 2006). As suggested in the literature (Garg & Kapellusch, 2009), this method might assess and predict WRMSDs risks better than questionnaire-based methods (Buckle & Jason Devereux, 2002; Garg & Kapellusch, 2009).

The information on energy transfer (Table 3) during operation is also invaluable. A person at rest has a constant energy consumption—a basal metabolic rate (BMR) expended in a neutral environment. An adult man requires, on average, about 1700 kcal (7000 kJ) and a woman about 1400 kcal (5900 kJ) per day (Hills et al., 2014). With work, depending on its intensity, the energy requirements of the body increase. The net energy cost in our experiment was related to the component lifting (and the change in potential energy, PE) and the development of angular velocities at the joints (kinetic energy, KE). The KE was dependant on the speed and had a low contribution to the total energy (compared to PE). In summary, the total energy expenditure (during the 30-min observation) was 5634.3 J/min (for MWE) or 4394.1 J/min (for AWE) on average, with the highest values for the average power reaching 6807.2 J/min (for MWE) or 5676.5 (for AWE). According to Lehmann's chronometric-tabular method, values in the range 3350–6280 kJ per shift for men and 2930–4187 per shift for women correspond to a moderate degree of work severity (Haggarty et al., 1997; Hills et al., 2014; Pałęga, 2019). The mean values in our measurement corresponded to the moderate level of work, but some of the workers (with Average Power of around 6800 J/min) fell into the severe work category posing a potential WRMSD risk factor.

This paper also presents a conceptual model of the interaction between the body parts and external factors influencing the musculoskeletal system (biomechanical load) during operations (Table 4). The main body parts' load was related to the moment of inertia and speed rate measured by the accelerometers. The extremal values of inertial loads were registered for the forearms (around 280 N) and the upper arms (~180 N), with a strong predominance of right upper-limb movements. The pelvis, loins, and thorax accelerations were relatively small, and did not influence the outcome loads. Regrettably, there are no corresponding EN or ISO norms concerning inertial loads. EN 1005-3 involves isometric forces (static loads), which could serve as a baseline for our measurements. E.g., it refers to forces of arms and forearms with values between 50-75 N, or the isometric force capacity limits (for actions for professional use) of 225-275 N during pushing and pulling with trunk support (EN 1005-3, 2002). By using the proposed biomechanical model, following quantitative verification, the relevance of this information to industry consists of providing safety levels that can result in improved work and protection for workers against WRMSDs. Intense physical workload, such as pushing, pulling, lifting, carrying, or manipulating a heavy load, is a common task leading to the development of WRMSDs (Limbong & Widajati, 2021; Pistolesi & Lazzerini, 2020; Roman-Liu, 2013). Particular tasks, like lifting and handling patients, especially with physical effort (Doda et al., 2020), also posed risks for the low back. However, even light manual work at an assembly line, such as packing small objects, etc., which mostly involves using upper limbs for repetitive tasks with a static load on the back, also causes musculoskeletal disorders (Bosch et al., 2007; Fu et al., 2019). Many systematic reviews have confirmed that repetitive and forceful upper-limb movements are risk factors for developing WRMSDs (Hanvold et al., 2019; Hulshof et al., 2021; van der Windt, 2000).

Based on the data analysis, it can be concluded that human movement analysis makes it possible to determine the level of somatic (physical and physiological) well-being. It accurately determines the level of load on the joints during the performance of activities at the workplace—its objective—and allows for the study of many variables. However, it is difficult to determine on the basis of this methodology whether we are dealing with overload in relation to the daily functioning of a person. The questionnaire method, which is the subjective opinion of the person being examined, complements a biomechanical examination. Undoubtedly, the use of both methods is most desirable and would allow for a comprehensive study of the level of well-being within the organisational environment. To a greater extent, these methods make it possible to create a forecast of the future state and recommendations for work ergonomics and work environments. Activities of this type also illustrate the need for interdisciplinarity in conducting scientific research.

Finally, it is worth noting that the various ergonomic workstation research tools, injury risk, or WRMSD, do not examine human movements comprehensively – in terms of all possible body parts or movements. For example, ranges of arm movements are carefully examined (RULA - Rapid Upper Limb Assessment), or the main parts and movements of the entire body (REBA - Rapid Entire Body Assessment) in terms of the selected neck, trunk, arms, legs and wrists positions or adjustments. Whereas the motion capture system objectively monitors all movements in terms of their amplitude, variability, symmetry and frequency, estimates segmental loads and energy cost, which is undoubtfully an added value of the motion capture technology for occupational health and safety innovations.

Limitations of the Study

The investigators took exceptional care to avoid sources of bias and confounding in their studies by eliminating movements unrelated to the studied work tasks. Still, a few movement artefacts may have remained when analysing long stretches of work associated with unpredictable interruptions or incidents during production and the work process.

Although characterised as having three degrees of freedom, the trunk's movements are quite constrained at a single vertebral level. The lumbar and thoracic areas of the vertebrae allow the trunk to flex and extend, but this plane of movement is limited in the middle thoracic portion of the vertebrae. Similarly, the rotation of the trunk occurs primarily in the thoracic regions because the lumbar region has limited movement potential in the horizontal plane. It is only the combination of all vertebral segments that allow the 3D movement produced by the spine. Moreover, the concept of total mechanical work based on the movement of the CoG does not characterise the work of different body parts.

The inertial load was calculated based on the central moment of inertia of a body part (along the central rotational axis) and involved only the body part without considering the weight of the handled component, which varied during the machining/assembly process. In this simplification, the mass of a component was negligibly small compared to the mass of a body segment. Studies investigating risk factors for the development of WMSD should report in detail the exposure levels. Individual risk factors associated with WMSD should be considered.

CONCLUSIONS

The analysis of ergonomics of human motion at work helps in improving workstations' ergonomics, increases workers' and organisational productivity, and may enrich H&S procedures. Human movement analysis makes it possible to determine the level of somatic (physical and physiological) well-being. The most valuable findings of the study, associated with risk symptoms in work-related musculoskeletal disorders, were the following:

- countermovement positioning of the pelvis with respect to loins for a prolonged duration, which could lead to back pain
- combination of median angle values and excessive body part load suggest overuse of joints throughout the whole working process
- the variation in movements, especially during flexion-extension and abduction-adduction on the left side, was high or very high, suggesting high upper-limb involvement
- low variation in movements of the pelvis, loins, and thorax suggests static posture during operations
- a strong predominance of right upper-limb movements

IMPLICATIONS FOR RESEARCH

As shown, the IMAS gives a wide variety of variables that could be measured and investigated in a workstation during everyday tasks. It allows H&S specialists and ergonomists to plan and organise work in accordance with healthy workplace standards. In terms of health and safety risk factors, the IMAS also enables in-depth analyses to reduce or even eliminate them. The results allowed us to generate recommendations for HR, H&S, and ergonomics procedures. Firstly, the method and findings might help improve workstation ergonomics, increase workers' and organisational productivity, enrich H&S procedures, and improve automation on production lines. Firstly, job rotation and methods-time measurement (MTM) might be improved. Secondly, health interventions, including physiotherapeutic exercises to prevent asymmetry and spine-related diseases, should be implemented. Finally, a company received detailed instructions on how to improve workstation ergonomics, including an in-depth analysis of workers' movements during manual handling, which can be used to complement the standard ergonomic procedures to avoid or reduce forceful exertion, awkward postures, and repetitive motion.

ENDNOTES

1. European Survey of Enterprises on New and Emerging Risks (ESENER), 2019, 45,420 establishments, EU 28 countries+ Iceland, North Macedonia, Norway, Serbia and Switzerland
2. Eurostat, Labour Force Survey ad hoc module 'Accidents at work and other work-related health problems' (2013).

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