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Digital assembly design with a motion capture system

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Abstract

It is important to consider ergonomic and productivity criteria at an early stage in the design of assembly workstations, when the design freedom and solution space is greatest. Also, if planning errors and improvement potentials are identified before the start of production, the costs of eliminating errors can be reduced significantly. Cardboard engineering is a lean method for designing workstations that integrates the expert knowledge of industrial engineers and the implicit knowledge of production workers. However, today established methods for analyzing ergonomics and productivity cannot be applied in cardboard engineering workshops because of a lack of data. This affects the design as many opportunities for improvement are not being identified and implemented. This contribution presents a concept to use these already established methods in cardboard engineering workshops by capturing the required data with a motion capture system and evaluating them using a digital assistance system. This makes it possible to increase the quality of assembly planning, improve documentation effort and quality and start the production ramp-up with ergonomically and optimised processes.

Keywords: assembly; motion capture system; digital assistance system

1. Introduction

The work result, productivity and health of employees are decisively influenced by technical, organisational and personnel factors of the work system [1]. The work system serves to fulfil a work task, whereby the workstation is the physical area in a work system in which the work task is performed [2]. The paper addresses the question of how work tasks and workstations in industrial assembly can be designed ergonomically and productively from the beginning in technical and organisational terms. This is important because an insufficient design of the work system can lead to a loss of productivity, e.g. due to unnecessary movements, or to musculoskeletal disorders due to excessive strain [3, 4]. According to a study by the Global Burden of Disease in 2019, around 1.7 billion people worldwide live with musculoskeletal disorders [5]. If measures for process optimisation or ergonomic workstation design are only implemented after the workstation has been implemented, the costs of eliminating these errors are significantly higher than if the measures are implemented during the workstation and process design [6]. There are also indirect costs if the employee is absent due to the incorrect workload or their performance is restricted in the short term or even permanently [4]. Cardboard engineering (CE) offers one possible solution. This involves physically simulating planned activities, processes and work system arrangements with the help of affordable, readily available materials. A key objective of CE workshops is to integrate the implicit user knowledge into workstation and process design [7]. As a result, planning errors and potential for improvement can be detected even before the production startup. Until now, process experts have only been able to use essential parts of their knowledge in CE workshops to a limited extent because many analysis methods are too complex and too time consuming for CE. The aim is to use a motion capture system to automatically record the data required for the analyses so that productivity and ergonomics analyses can be carried out very quickly to increase the quality of assembly planning, improve documentation effort and quality and start the production ramp-up with ergonomically and optimised processes.

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2. Current state of research

This chapter describes the state of research in cardboard engineering, digital assistance systems, motion capture systems and ergonomics analyses.

2.1. Cardboard-Engineering

Traditionally workstations are often designed by industrial engineers at their desks and the employees who will later work at the workstation are often excluded from the decision-making processes. This can lead to lower levels of acceptance and motivation from employees. Moreover, it is not possible to use the valuable implicit knowledge of employees about production [3]. A core idea of the CE is therefore to involve the employees interactively in the detailed planning of the assembly and to validate the developed concept in a realistic setting. In many companies, this method of participative workstation design is an important link between the initial rough planning of assembly and the implementation of the improved planning standard. In the first stage of CE workshops, the assembly operation is clarified and the assembly concept is detailed. In the second step, a workstation is modelled using simple and affordable materials. In the third step, the assembly is simulated and optimised as part of cyclical improvement loops [8]. Even though in these workshops usually processing times are measured and basic key figures are calculated, the applied analysis methods are simple [3]. As a consequence, established methods for ergonomics and productivity cannot be applied. In [9], for example, it is pointed out that gripping movements can be represented by threads or walking paths can be drawn on the floor. Collecting data in this way requires a high level of manual effort. Documenting the improved planning standards is also complex. In a case study in [6], the results are documented using photos with dimensions and process descriptions. In [9], the processes are documented using a standard worksheet or a standard work combination table. Another aspect is that in the documented CE workshops, only productivity was analysed, not ergonomics [6, 9].

2.2. Digital assistance systems and motion capture systems

Digital assistance systems support employees in their activities in a targeted and learning-promoting manner by providing application-related and real-time information. This information helps employees to make decisions [10]. In the field of assistance systems, there are already studies on further training with digital assistance systems or on the coordination of maritime interior design with digital assistance systems [11, 12]. Digital assistance systems can also be used in combination with technologies such as augmented reality. In this context, [13] shows how the effort required to obtain information in one-off production can be reduced, thus increasing productivity.

Motion capture technologies capture and document movements and transfer them to a digital human model [14]. There are various methods of motion capture, such as optical, electromechanical, electromagnetic and acoustic systems [15]. In this research a motion capture system from Xsens is used, which is an electromechanical system. In this tracking suit, the worker is equipped with 17 motion sensors with inertial and magnetic measuring units that include 3D gyroscopes, 3D accelerometers and 3D magnetometers. The motion capture system determines position and orientation data and sends it wirelessly to a receiving station at a maximum of 60 Hz [16]. This data are used for productivity and ergonomics analyses in the CE workshops.

The CE method has also already been digitalised. However, the approaches are limited to a CE using virtual or augmented reality [17, 18, 19].

2.3. Ergonomics analyses

A stress-strain analysis is a proven concept for evaluating work conditions. Ergonomics is defined stress as the external characteristics of the work situation, such as the work task and physical, chemical, organisational and social environmental conditions. The concept of strain includes the reactions to stress, e.g. physical-physiological. The strain depends not only on the load, but also on individual characteristics and abilities such as the person's qualifications. The same stress will cause different strain in different people. The type of stress can be both situation-related and task-related [20]. [21] has developed an employee-specific analysis of work-related stress, combining the individual abilities of employees with the requirements of the workstation. The focus of this study is primarily on analysing and evaluating stress. This is done using various assessment methods which can be roughly differentiated in terms of the assessment level and the type of stress. The assessment methods can be divided into rough screening methods, screening methods, detailed/expert methods and measurement methods. The load types include various types of manual load handling, action forces to be applied, postures and movements forced by the activity or loads on the finger-hand-arm system caused by repetitive activities with high repetition frequencies [4]. The main target regions of the body are determined for each type of stress. For example, manual work processes primarily place stress on the shoulders/upper arms, elbows/forearms and hands/wrists [22]. Various stress-relevant parameters can help to minimise stress in the planning stage of a work system. In the area of process planning, these include, for example, the assembly concept/layout or the work sequence. In the area of workstation design, the working height/depth and environmental influences are important parameters for preventively avoiding high levels of stress [4]. Various studies have investigated whether and how these procedures can be automated with an electromechanical motion capture system and what advantages and challenges arise compared to manual execution [23, 24].

2.4. Research gap

The analyses automated by mocap systems are isolated and applied to existing workstations. This leads to two problems:

1. correlations between areas such as ergonomics and productivity are not identified.

2. if the errors are detected during the running production, this leads to high error elimination costs.

A solution is to use established methods of ergonomics and productivity in CE workshops. The goal of this contribution is to present a concept that uses a motion capture system to capture the required data and a digital assistance system to evaluate the data in order to provide workers and process planners with the results of the ergonomics and productivity analyses in a short period of time during CE workshops. This enables the design of optimized workstations even before production starts.

3. Concept

To develop a concept that can be used in CE, requirements for the analysis methods and requirements from the CE must first be defined. The restrictions that must be considered when implementing the requirements for developing the concept are then explained. The concept is presented in the last part of this section.

3.1. Requirements for the analysis methods

The requirements for analysis methods cover various aspects relating to both ergonomics and productivity. For ergonomics, it is important to use methods that allow the physical stresses to be assessed that frequently occur in industrial assembly. If possible, the interpretation of the results should also be comprehensible even without a deeper knowledge of ergonomics. In the area of productivity, methods should be used to identify influences on working time and minimise waste. When selecting productivity and ergonomics analyses, attention should be paid to the type of production. In mass and series production, for example, often the MTM-1 method is used and the strain is analysed with regard to posture. In make-to-order production, on the other hand, the MTM-UAS or MTM-MEK method tends to be used and loads are analysed with regard to load handling [25, 26]. It should also be possible to add metadata to all analysis methods. Once the analyses have been completed, the results should be easy to retrieve with an intuitive access logic. A comprehensive view of the analysis results is achieved by aggregating productivity and ergonomics indicators at various levels of detail. It is important that the interactions between ergonomics and productivity can be made clear at each level of detail. In addition, a clear and comprehensible visualisation of the results is required. A structured documentation of the analysis results is necessary to ensure that the findings are usable and available in the long term.

3.2. Requirements from Cardboard Engineering

In order to be able to analyse ergonomics and productivity during or at least immediately after the execution of assembly operation, a high recording and analysis rate is required. It is also important to highlight critical work steps, for example if stress variables exceed acceptable limits or to show large deviations between target and actual process times. Identifying critical values makes it possible to make quick and targeted improvements and adjustments. Finally, to ensure a continuous improvement process, automatic process documentation of the improvement loops in the cardboard engineering workshop is essential.

3.3. Restrictions and challenges

The position data provided by the motion capture system is subject to drift, as it is determined from the measured acceleration by double integration over time. Extensive reprocessing across the entire data set is thereby required and computed by the Xsens software [16]. A detailed productivity and ergonomics analyses can therefore only be executed after this reprocessing. The duration of reprocessing depends on the length of the assembly process. A further limitation is that methods for analysing stress types such as static postures cannot be performed in real time. The analysis results are therefore only available after a assembly process has been completed. Furthermore, analysis methods cannot be automated if the subjective knowledge of an expert is required to a high degree. Also, extensive metadata should not be required for the analyses, as this slows down and complicates the execution of the CE workshops and consequently reduces the degree of automation. If metadata is replaced by assumptions, it is important to ensure that the validity of the results is guaranteed.

3.4. Basic concept

The concept is divided into a live analysis, which is displayed during the motion simulation, and a process analysis, which is available after reprocessing the data following a motion sequence. The concept developed in this study is designed for mass and series production in industrial assembly. The methods used in the live analysis and the process analysis are listed in Figure 1.

	Ergonomics	Productivity
Live analysis	• Joint angle • Handling area	
Process analysis	• Measurement analysis to determine unrecommended body postures	• MTM-1 method • Primary-secondary analysis • Line Balancing

Focus of this paper

Fig. 1. Basic concept

In mass and series production, physical stress is often caused by incorrect body postures. Thus, for the live analysis, the real-time measurement of joint angles and handling areas were selected as analysis methods, as these allow an initial assessment of the postures in real-time without the need for further metadata. Many ergonomics analyses, such as the Rula method, were developed at a time when mocap systems were not common. Consequently, they are designed as observation methods that are carried out by experts and require expert knowledge. The proposed analysis is based on measurements of the mocap system database and takes into account parameters that could not be captured in the past. To analyse productivity, methods designed for mass and series production are also used. However, these are not discussed in this paper, as the focus is on ergonomics.

3.5. Live analysis

With the live analysis, indications of unfavourable postures are obtained in real-time. For this purpose, the measured joint angles are compared with the angular ranges of various body joints specified in [27] of the German Social Accident Insurance (DGUV). For the head, trunk, upper and lower extremities, the parameters, directions of movement and the literature used for categorisation are specified in this DGUV Guideline. Figure 2 shows this information as an example for the shoulder joint, which has three degrees of freedom.

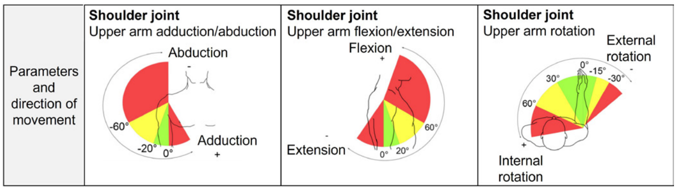

Fig. 2. Angular ranges of the shoulder joint according to [27]

The angle ranges are categorised according to the traffic light system. Taking into account the physiological range of motion, the angle categories are categorised as neutral or acceptable (green), mid-range or conditionally acceptable (yellow) or end-range or unacceptable (red). However, in addition to the values for the joint angles, the categories are also subject to other secondary conditions. These include the duration, frequency and dynamics of movements or the statics of postures and external circumstances (e.g. upper body or arm posture supported). These conditions must also be taken into account when assessing postures [27]. This is done as part of the subsequent process analysis.

A handling area analysis is another way of identifying unfavourable postures. Handling areas are areas around a person in which objects can be touched, grasped or altered without a significant change in posture [28]. The defined handling areas can be helpful when setting up and arranging workstations. The handling areas are basically determined by the anatomical characteristics of the employee and by the specific activity with its boundary conditions. They therefore often only apply to clearly defined cases [20]. According to the VDI manual, the handling area can be divided into a geometrically maximum handling area, a physiologically maximum handling area and a small handling area. The geometric maximum handling area is defined as the area that can be accessed with a motionless upper body, with the arm extended to the maximum and by moving the shoulder joint. The physiologically geometrically maximum handling area is defined as the area that can be accessed with a motionless upper body, a relaxed arm and no movement of the shoulder joint. This handling area is particularly important in practice and is around ten per cent smaller than the geometric maximum handling area. The small handling area is recommended for frequently recurring grip movements. This is defined by the space created when the upper body is motionless with the upper arms hanging down and, if necessary, the forearms supported [29].

3.6. Process analysis

The ergonomics analysis is a measurement-based assessment method to determine the percentage of time spent in non-recommended postures/movements. This assessment procedure was developed as part of the MEGAPHYS joint project of the Federal Institute for Occupational Safety and Health (BAuA) and the DGUV. The aim of the procedure is to determine the percentage of time during an activity in which unrecommended postures or movements are assumed. This applies to various regions of the body, such as the neck and cervical spine, the shoulders and upper arms (left and right), the elbows and forearms (left and right), the hands and wrists (left and right) and the lower back and lumbar spine. Various aspects are taken into account during the assessment, such as the intensity of the movements, the angular ranges, the duration of the postures, the type of activity, the support of body parts and the combination of movement directions. For each data point, the assessment procedure checks whether the posture/movement is acceptable or unacceptable for the respective body region. In addition, a cumulative value is determined that indicates the percentage of time spent in unrecommended postures and movements per activity [30]. This value is then categorised into four risk categories according to the general risk concept of MEGAPHYS [22].

4. Implementation and evaluation

For the implementation of the concept, an IT system is used, the architecture of which is explained in the first part of this section. Building on this, the implementation and evaluation of the live analysis and process analysis is described.

4.1. IT system architecture

To reduce dependencies on native software, a web-based IT system architecture has been implemented that is easily accessible across different end devices. The system architecture is outlined in Figure 3.

The IT system architecture includes three central elements: **Motion capture system:** The motion capture system is used in combination with a Python programme that runs locally on an end device such as a laptop. This Python programme integrates the Xsens software development kit to interact with the motion capture system without requiring the Xsens software to use the motion capture system. The Python programme is connected to the IoT platform via a network protocol and enables bidirectional data transmission.

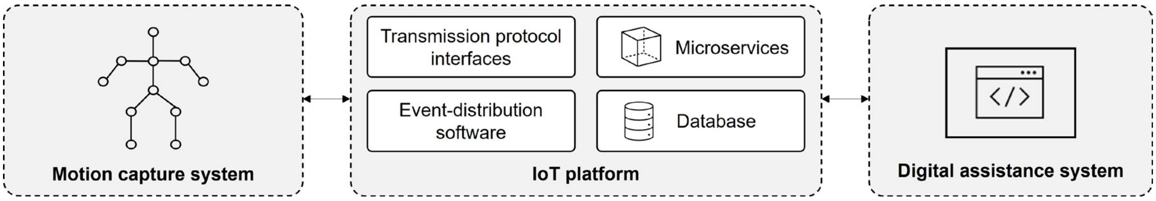

Fig. 3. IT system architecture

IoT platform: The IoT platform is a central element of the IT system and provides the connection between the digital assistance system and the motion capture system via various interfaces and network protocols. The data flow between the different modules of the IoT platform is controlled by an event streaming software. The architecture comprises various modules, including microservices and a database. Productivity and ergonomics analyses are run as microservices. The results of the analyses can be stored in the database along with other information. All platform modules are implemented as containerised applications and provided on a cloud-based cluster.

Digital assistance system: The digital assistance system enables the user to run live analyses and process analyses on the web. The user interface provides a bidirectional connection to the IoT platform, via which important process data can be entered and results can be accessed and visualised. An advantage of the digital assistance system in combination with the motion capture system is that information from workpieces or tools, such as weights, can be assigned to the replicated objects in CE. This makes it possible to assess the real ergonomic stress of the assembly processes, even if the workpieces and tools are not available in the CE workshop.

4.2. Implementation of the live analysis

The joint angles are visualised in real-time on the digital assistance system as gauge charts. This is shown in Figure 4 as an example for the head inclination.

The illustrations in the centre of the gauge charts are static and are taken from [27]. The values in the gauge charts change dynamically with the movement and the bars in the gauge charts are colored red, yellow or green depending on the angle range. The analysis can also record the percentage of time each body joint is in the unacceptable range. This makes it possible to identify the joints that are under the most strain during the work task.

The live analysis includes a digital human model that is created in real-time from position data. In this environment, the geometrically maximum handling area is displayed for both sides of the body, which is created individually for the worker based on the body measurements. The limitation of the handling area is based on the maximum deflection angles of the shoulder in the various body axes in accordance to [31]. Only the geometric maximum handling area is displayed, as it is assumed that an unergonomic posture must always be adopted when reaching points outside this handling area. The position data of the hands can be used to determine whether the hand is inside or outside the handling area. As soon as the hand is outside the handling area, the handling area of the corresponding hand is coloured red, otherwise green. If the person moves around the room, the handling area can be updated via a button and thus realigned. Figure 4 shows the digital human model and the handling area of the right side of the body.

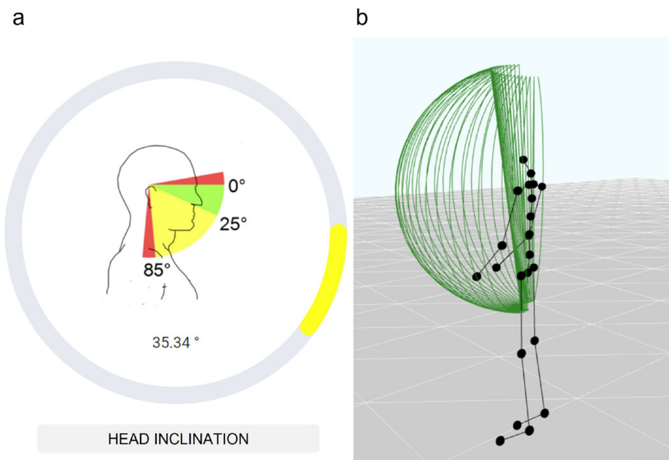

Fig. 4. (a) Gauge chart; (b) Handling area.

4.3. Evaluation of the live analysis

The live analysis has been evaluated in two companies. The first company operates in the medical and safety technology sector. The system was used in the area of packaging a measuring device, as employees reported health problems in the neck and shoulder area. Three measurements were performed, in each of which five measuring devices were packaged. The results show that the angles of radial/ulnar flexion of the wrist are in the unacceptable range for a large part of the work process. This problem is task-related and not related to the workstation design. Furthermore, the angles of flexion and extension of the elbows were found to be largely outside the acceptable range. This may be due to an incorrectly adjusted table height, although the table at the workstation is already height-adjustable. The handling area analysis showed that the hands were largely outside the handling area during the joining operation that took place on the table. This clearly shows the connection between the handling area and the acceptable postures. The problems in the neck region correlate with unfavourable angles of the head inclination. Possible reasons for this problem could be an incorrectly adjusted table height or materials placed too high.

The second company is a manufacturer of mechanical and electronic drive systems. Here, the system was used during the assembly of a small gear unit. The employees experienced health problems in their wrists, which were attributed to the operation of a punch to press a ball bearing into the gear unit. The punch is used about 25 % of the time in the work process. Figure 5 shows the workstation.

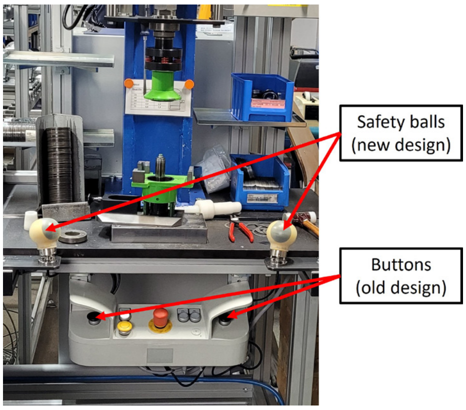

Fig. 5. Workstation for gear assembly in the industry

Originally, the press was operated by pressing two buttons under the work surface. In the meantime, ergonomic precautions have been taken by installing so-called safe balls, which are used to activate the press. Three measurements were taken at the old workstation and three measurements at the new workstation with the safe balls, where three gear units were mounted in each case. The results of the live analysis show that the new workstation design can significantly reduce the angles of flexion and extension of the wrists. However, the angles of flexion and extension of both elbow joints were conspicuous, which can be explained by an incorrectly adjusted table height. In addition, the flexion and extension angles of both knee joints were outside the acceptable range for a large part of the time. A standing stool could help to relieve the strain on the knees.

4.4. *Implementation of the process analysis*

The digital assistance system enables the administration of parts lists, assembly plans, employees and operating resources as a basis for the process analysis. The ergonomic analysis for evaluating unfavourable postures was implemented in a microservice that is still running in isolation and whose results are to be linked to the movement elements.

4.5. *Evaluation of the process analysis*

So far, the ergonomics analysis for assessing unfavourable postures has been evaluated in our model factory during the assembly of a gear. Figure 6 shows a section of the work system, which consists of two workstations.

The workstations were designed without ergonomic considerations. Table Figure 7 shows the results of the ergonomics analysis for the individual body regions.

Fig. 6. Workstation for gear assembly in the model factory

Target region	Time spent in unrecommended posture/movement [%]
Head	1.7
Upper arm left	6.3
Upper arm right	17.6
Elbow left	5.7
Elbow right	9.6
Wrist left	10.7
Wrist right	11.0
Trunk	0.6

Risk category
1
2
3
4

Fig. 7. Risk values of the body regions for gear assembly in the model factory

Table 1. Composition of the risk value for the right upper arm

Angle range	Movement intensity	Unrecommended posture/movement of the right upper arm [%]
Mid-range	Static	65.9
Mid-range	High dynamic	17.0
End-range	Dynamic	16.5
End-range	High dynamic	0.6

The only noticeable value is that of the right upper arm, which is calculated from the recorded data of the flexion/extension movement of the right shoulder joint. On closer examination of the composition of this percentage value, Table 1 shows that it is primarily caused by a static posture and mid-range angles and high dynamic/dynamic movements for mid-range/end-range angles.

5. Summary and outlook

This study presents a concept that uses a motion capture system and a digital assistance system to enable ergonomic and productive workstation and process design in CE workshops. To develop the concept, the requirements and restrictions are determined. The concept includes a live analysis, which is displayed during the movement simulation, and a process analysis, which is performed after the recorded data has been processed using more extensive analysis procedures. Partial functions of both analyses have already been implemented and evaluated, with the focus in this study being on ergonomics. The results of the live analysis show that the measured joint angles and individual handling areas provide initial support for ergonomic workstation design. The evaluation of the sequence analysis has confirmed that a measurement analysis to assess unfavourable postures is possible with the system.

The limitations of previous studies are that, in addition to the ergonomic assessment of postures, other types of stress, such as repetitive tasks, are also decisive in determining a risk value for the ergonomics of the workstation. Furthermore, no comprehensive investigation was carried out into the dependencies between the results of the live analysis and the measurement analysis. With regard to this, a simplified individual ergonomics analysis for postures could possibly be developed that utilises any correlations. In addition to ergonomics, the implementation of productivity analyses is required in order to obtain an evaluation together with the information from the work system that enables a simultaneous assessment of productivity and ergonomics at different levels of detail.

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