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Interactive production planning and ergonomic assessment with Digital Human Models – Introducing the Editor for Manual Work Activities (ema)

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Abstract. The aging workforce is a risk factor for manufacturing industries that contain many jobs with high physical workloads. Thus, ergonomic risk factors have to be avoided in early phases of production planning. This paper introduces a new tool for simulating manual work activities with 3D human models, the so-called ema[ϕ]. For the most part, the ema[ϕ] software is based on a unique modular approach including a number of complex operations that were theoretically developed and empirically validated by means of motion capturing technologies. Using these modules for defining the digital work process enables the production planner to compile human simulations more accurately and much quicker compared to any of the existing modeling tools. Features of the ema[ϕ] software implementation, such as ergonomic evaluation and MTM-time analyses, and the workflow for practical application are presented.

Keywords: Human Modeling, Production Planning, Proactive Ergonomics, Efficiency

1. Introduction

Manufacturing industries are facing major challenges due to the continued aging of their workforce, which is caused by an increasing life expectation and decreasing fertility rates. The demographic development is particularly considered as risk factor for work tasks that are associated with low autonomy and high physical task demands, for example automotive assembly [1], [2]. In order to keep the work-ability of older employees and avoid work-related musculoskeletal disorders, such as severe low back pain and carpal tunnel syndrome, manufacturers need to regard ergonomic principles of workplace design in early phases of production planning [3], [4].

Computer-aided simulation tools, such as digital human models (DHM), are considered to be very promising in the facilitation of pre-production planning and proactive ergonomic assessment [5], [6]. However, current DHM tools are often very complicated to handle and thus, it is mostly very time-consuming and inefficient to prepare human simulations for specific areas of application. Furthermore, it is important to assure that simulations of cycle times and ergonomic workloads are very precise and reflect reality quite well because analyses results may lead to substantial investments in workplace (re)design [7]. Facing these practical requirements this paper will introduce the “Editor for Manual Work Activities” (ema) – a new software tool that reduces the effort for preparing simulations of human work and, at the same time, improves the accuracy of simulations. ema can be applied in various manufacturing environments with clock-cycled assembly lines and manual work stations, particularly in the field of automotive production planning

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2. Theoretical and Empirical Background

The newly developed software tool "Editor for Manual Work Activities" (ema) uses a modular approach for describing and generating human work activities. ema is based on "complex operations" representing an aggregation of single elementary movements that are directed at carrying out a certain work task. Using such highly automated algorithms ema strongly reduces the effort for simulating human work enabling the production planner to generate a simulation of the entire work process by describing operations on a rough abstraction level. In order to achieve correct simulation results, all operations were deducted theoretically and then empirically validated.

2.1. Theoretical Considerations

Current tools for human work simulation, such as DELMIA Human Builder (previously known as Safeworks) and Siemens NX Human Modeling (previously known as Jack), often result in non-realistic dynamic movements. In order to improve the accuracy and validity of simulation results as well as the user acceptance human behavior and motions need to be generated and presented more realistically. Therefore, all movements of the human model have to be based on the principles of biomechanics and ergonomics (i.e., anthropometrics).

However, following these principles is not quite sufficient because both scientific disciplines do not specifically refer to the generation of realistic motions. Biomechanics investigates human abilities to carry out specific activities based on the functions of the musculoskeletal system and the law of physics [8]. Ergonomics examines the level of physical strain, including factors like body postures, action forces, and manual weight handling, when people are conducting a specific task in a specific work environment [9]. In reality, however, human movements in a work setting are not only determined by biomechanical abilities and ergonomic strain but also by a number of other influences.

People tend to carrying out work tasks in the most convenient and most comfortable way. Eklund, for instance, found that people put less effort in correctly performing their work tasks when they felt fatigue or pain in body parts in order to avoid discomfort [10]. Nevertheless, the most convenient way is not necessarily the most ergonomic way of working and thus, people often need to be trained to move correctly, for example when lifting heavy parts. This is the reason why many human movements in a production environment are strongly influenced by the training level of operators according to the standard work descriptions that are pre-defined by supervisors. Thus, for example, people might use their left hand instead of the right hand not because it is easier – but because it avoids injuries and it is requested by their standard work description.

Based on these theoretical assumptions and practical observations the artificial generation and simulation of correct and realistic human movements at work has to consider at least three factors: (1) biomechanical principles, (2) ergonomic strain, and (3) the training level of real operators. For the development of the new ema$^{\phi}$ software all three factors were investigated, as will be described in the following sections.

2.2. Defining Complex Operations

ema$^{\phi}$ utilizes a modular approach for describing and generating human work activities that is based on so called "complex operations". Complex operations represent an aggregation of single elementary movements that are all directed at carrying out the same work task in a logical sequence. For instance the operation "get and place part" may consist of the following single movements: steps forward – bend – hand to object – pick object – object to body – step backward – turn – steps forward – bend – place object – let loose – hand back. Of course, in a multifaceted work environment like automotive assembly many complex operations are needed and most of them are more complicated than the example above.

One major challenge in the development of ema was to define and implement all the complex operations and each single step in the correct sequence. At first, operations were logically defined based on theoretical analyses and practical observations. The most complicated part, however, was the software-technical implementation of each operational step. Particularly, a number of parameters were defined for each complex operation enabling the software user to quickly adjust the boundary conditions of the work task, for instance the weight of the part that has to be handled. Thereby, large efforts of research, analyses, and testing were invested to optimize the algorithms for each operational step in accordance with biomechanical and ergonomic principles in order to improve the correctness of movements under the given physical restrictions. To this end, the software developers also used motion-capturing data from real operators with a certain training level.

2.3. Empirical Validation with Real Operators

Currently there are no sufficient theoretical methods that are able to fully describe the complexity of the generation of human motions. Therefore, an empirical approach that uses the movements of real humans is needed in order to develop more realistic simulation methods. Modern technologies of motion capturing are able to record movements in space and describe it as three-dimensional vectors. In this way, it is possible to collect reliable motion data that can be used for enhancing the quality of the software-technical generation and simulation of human movements.

In this project, an A.R.T. (Advanced Realtime Tracking) motion-capturing-system was used for the development of ema to specifically record human movements when performing pre-defined sequences of manual work activities. In order to collect motion data that can be used for the purpose of realistically generating and simulating human work it was necessary to prepare an artificial environment in which experienced operators from real production lines are recorded and real standard tools, such as battery-driven screwdrivers, are used. Based on these premises a large number of trials were set up to motion-capture simple sequences, such as "get and place part", as well as more complex movements, such as "car ingress/ car egress". Thereby, a number of external parameters that may influence the recorded movements were systematically varied and tested; for instance the working height, the force direction, and the weight of the handled parts. Furthermore, the characteristics of study participants were also varied, particularly the body height and the skill level. Finally, the following conditions were found to be most useful for recording motion data that can be used for human simulations in pre-production planning:

- Capture close-to 50^{th} percentile body height
- Use skilled worker with much experience and training in the simulated task
- Record operations in very small steps and systematically varying parameters
- Identify continuous behavior, erratic movements, and impossibilities/refusal

Based on these premises studies were conducted with experienced skilled workers at the Volkswagen Training Center in Germany. Before recording motion data for the complex operation "screwing with battery tool", for example, all possible screwing directions and angles were deducted from theory and expertise considering influencing factors, such as the working height. Based on this, a test specimen was prepared that contained 181 drilled holes in a range of more than 180 degrees. Following that, some test trails were conducted to determine the exact separation and sequence of recordable movements. Finally, after an elaborate phase of preparation, the actual motion capturing trails took place.

After recording motion-capturing data have to be reprocessed in order to eliminate measurement inaccuracies, numerical errors, missing markers, etc. Following that, all data needs to be translated into 3D vectors and related to a specific model of the test participant, in which all movements are described by joints. In a second step, individual motion data has to be enriched with meta-data for categorization and stored in a common database for typed movements. Finally, this database is the source for the motion generator that is used by ema to simulate complex operations following the principle of similarity: individual movements for specific conditions are derived from the database by searching the best match (i.e., the most appropriate and most similar motion in storage). This mechanism is a very complex procedure that is based on many algorithms and represents the actual "heart and brain" of ema.

2.4. Ergonomic Risk Assessment with ema

Biomechanical correctness and a high accuracy of movements were both important criteria for finally defining and implementing the complex operation modules in ema. Thus, using the pre-defined operations by specifying external parameters for compiling digital human simulations not only reduces the time-effort and enhances the simulation efficiency, but also enables the production planner to conduct more precise ergonomic evaluations [6].

ema has included a standard tool for ergonomic risk assessment, the AAWS ("Automotive Assembly Worksheet") [11], respectively its updated format EAWS ("European Assembly Worksheet"). This checklist has been shown to produce reliable results in real-world settings as well as in the evaluation of digital human simulations [7]. It was specifically developed for ergonomic assessments in repetitive assembly tasks. In contrast to other methods like RULA [12] or OWAS [13], which are both mainly focused on postures and already available for DELMIA Human and Siemens Jack, the EAWS includes several physical risk factors, such as static postures, action forces, manual weight handling, and specific "extra work strains". Moreover, EAWS systematically takes the intensity, duration, and frequency of all four risk factors into account and thus, allows a more comprehensive ergonomic evaluation of the entire assembly process.

Using the EAWS methodology as foundation ema enables a semiautomatic ergonomic assessment, which improves not only the efficiency but also the objectivity of 3D human work analyses. To this end, the joint angles and positions of the body segments are recorded throughout the entire cycle (i.e., simulation time). Based on this data each posture is categorized into one of the standard posture classes as defined by EAWS (e.g., standing upright, bend forward, overhead, etc.). In some situations the categorization based on the joint data is not quite definite; for instance, when sitting on an assembly chair the joint positions of the legs may be very similar to a squatting posture. However, the modeling methodology of ema facilitates correct posture assessment for such cases because it assigns an initial body movement that is typical for each posture; for example, there is always a movement to "sit down" prior to the posture “seated”. This approach ensures a correct and definite automatic categorization of all postures.

Moreover, certain complex tasks, such as “car ingress / car egress”, may contain further workloads leading to additional scores for “extra work strains”. To complete ergonomic evaluation, information regarding action forces and objects weights need to be manually included by the user. Finally, ema combines all ergonomic data and calculates a total risk score that is rated according to the traffic-light system (green – yellow – red) defined by EAWS. This way, ema allows a comprehensive semi-automatic ergonomic assessment by using automatically retrieved data on postures and movements that are slightly enriched with additional information on forces and weights provided by the user. However, in future releases ema will also enable to automatically retrieve this kind of data from CAD part specifications, when available.

3. Practical Application of ema

ema$^{\phi}$ was already tested in a number of pilot applications in car manufacturing. First results show that ema$^{\phi}$ can reduce the effort for preparing human simulations up to 90% compared to manual step-by-step simulations. Most importantly, the first pilot applications showed that ema$^{\phi}$ can be integrated in corporate software architecture to support the standard product development process that is used by several car manufacturers as well as other production industries.

Firstly, in the early concept phase ema$^{\phi}$ may be used to validate the product buildability, which includes the verification that the vehicle can be manufactured with the given planning premises, equipment restrictions, and abilities of manual operators. Ergonomic analyses in that phase can, for instance, check well-known issues of the predecessor car (i.e., the reference vehicle) and other previous models. ema$^{\phi}$ supports this phase by using available CAD-data to quickly set up human simulations for comparing concept alternatives that influence the future assembly process. Thus, part design might be revised to improve the ease of manual assembly, which may not only reduce ergonomic workload but also save costly production time. By enabling accurate 3D analyses of the future assembly process ema$^{\phi}$ may also significantly reduce costs for late corrective design changes and part optimizations after start of production (SOP). Furthermore, ema$^{\phi}$ provides the opportunity to visually document good design solutions in a database for best practices that could be used as guideline for the development of future models.

Secondly, in the phase of pre-production planning ema$^{\phi}$ may be used for the compilation and validation of the future work process. Utilizing the features that were described above ema$^{\phi}$ supports the production planner to quickly set up a standard work sequence and generate 3D simulations for visual inspection and optimization. ema$^{\phi}$ provides a set of tools that facilitate the design of efficient work processes by avoiding “waste” (with reference to the Toyota Production System), such as ergonomic strains (far reach, bending, etc.), long walking ways, and double-handling of parts and tools. Thus, ema$^{\phi}$ enables to compare process alternatives by means of objective quantitative analyses on ergonomics and MTM-time in early phases of pre-production planning merely based on digital product data that is readily available in the existing PLM environment, such as DEMLIA V5.

Finally, in the phase of series production ema$^{\phi}$ may be used for investigating product, equipment, and process optimizations before implementing the actual changes to the production line or setting up costly production trials. In order to support the continuous improvement process after SOP ema$^{\phi}$ allows the series planner to quickly simulate and verify the integration of new concepts in an existing production environment. Again, the incorporated tools for quantitative analyses on ergonomics and MTM-time provide an objective evaluation of the proposed changes and thus, the costs for extensive production trials decrease. Furthermore, the ema$^{\phi}$-generated simulation can be used to communicate evaluation results to the involved parties, such as the workers union, safety experts, plant management, etc., and reach a common sense on the final solution. At last, the same simulations can also be used to introduce the new equipment to the workers and provide a first training on the correct usage and the new work processThe newly developed software tool "Editor for Manual Work Activities" (ema) uses a modular approach for describing and generating human work activities. ema is based on "complex operations" representing an aggregation of single elementary movements that are directed at carrying out a certain work task. Using such highly automated algorithms ema strongly reduces the effort for simulating human work enabling the production planner to generate a simulation of the entire work process by describing operations on a rough abstraction level. In order to achieve correct simulation results, all operations were deducted theoretically and then empirically validated.

4. Practical Application of ema

ema$^{\phi}$ is a new tool for simulating and editing manual work activities in digital production planning. Based on a large body of research ema$^{\phi}$ improves simulation accuracy of existing man-models, such as DELMIA Human, and significantly reduces the effort for compiling human modeling studies using unique modules of complex operations. ema$^{\phi}$ enables the human model to quickly transfer standard work descriptions into sequences of natural movement – just like a real operator would do. In that sense, ema$^{\phi}$ makes the human model a little bit smarter by utilizing the skills and the knowledge of a qualified worker. Finally, ema$^{\phi}$ supports production planners in analyzing future ergonomic conditions and avoid physical overload proactively in order to keep the work ability of the aging workforce in manufacturing industries.

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