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A generic hybrid Human/Exoskeleton Digital Model towards Digital Transformation of Exoskeletons-integrated workplaces

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Abstract

The Exoskeleton represents a promising technology aiming to improve physical and organizational ergonomics in manufacturing reducing the physical fatigue, thus enhancing cognitive ergonomics. The foundations of digital transformation of human-centred workplaces with integrated Exoskeletons have been well researched by the group, coping currently with the challenge of optimizing the ergonomics simulation parameters and embedding the Exoskeleton controller in simulation systems. A methodology of capturing in real-time workers' physiological status wearing active and passive Exoskeletons, data interpretation and aggregation towards developing a hybrid human/Exoskeleton Digital Model represents the current work of the group. The performed experiments developed model and validation in several use cases for assembly and logistics activities are reported.

Keywords: wearable robotics; workplace ergonomy; exoskeletons; digital twinning;

1. Problem statement

The domains of heavy industries, constructions and logistics are some of the most challenging areas of activities from the physical point of view. The human workers are essential in these industries, even with the rise of automation, since certain segments of the market are specialized on low series of products, or have a wide range of different products, which make the automation infeasible. The workplace is designed to decrease the strain on the human worker. Even with these advancements, the manipulation of heavy loads, the exposure to high vibration and the hazardous environment of certain workplaces are impossible to be removed or even reduced in certain cases.

One of the solutions for this challenge is the exoskeleton technology, which have the potential to improve the ergonomic state of certain workplaces. The integration of these devices is mainly done directly with "on site" studies, with high costs and long-term procedures. The existing simulation software with ergonomic analysis capabilities lack the required tools for a Digital Twin of the human-Exoskeleton discreet interaction.

Process flow disrupting technologies are emerging on the market, as a reaction, the frameworks for Digitalization for widely accessible technologies such as Virtual Reality (VR) [1] can be used as a foundation for the digitalization of the exoskeletons, once a comprehensive methodology of integration is available.

In the following chapters the foundation of a generic methodology of digital integration of the exoskeleton in the workplace and the beginning of hybrid worker digitalization are conceptualized and first steps are realized.

As main resource towards the Digitalization, an ergonomic-organizational simulation tool (Jack and Advance Human by Siemens) is used. The innovation consists in the direct ergonomic analysis over the coupled human with exoskeleton and the traditional ergonomic tools preexisting in Jack. The method precedes the industry-enabling tool for direct human

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exoskeleton interaction, which would result in the overcome of exoskeleton integration issue.

2. State-of-the-art and challenges

2.1. Ergonomic state of the workplaces

The largest European Occupational Health Survey published that the most common work-related health issues are the back pain, which affects 46% of the workforce and neck, shoulders, and upper limbs pain with 43% [2]. Between 2007 and 2013 the percentage of workers reporting musculoskeletal disorders increased from 59% to 62% [3]. The development of such conditions often cannot be confined to a single cause and their prevention can only be successful if the work-related aspect of the cause is reduced. In work-related health problems, the number of days lost to illness is estimated to be 1.6 to 2.2 times higher than the days of temporary incapacity to work caused by an accident [4]. One preliminary explanation for this is that these disorders develop insidiously over time. Longer-term health impairments and chronic illnesses increase with age. Given the demographic changes, especially in the developed countries, the significance of such topics as workplace safety and health for labor market policy is going to increase considerably in the future.

2.2. The industrial Exoskeletons

Known as the Operator 4.0 [5], or the Hybrid worker – the Exoskeleton equipment and the wearer are a new concept in the industrial area, which provides the flexibility and intelligence of the human worker, while it projects the endurance and precision of the machine. Human-exoskeleton worker is on the verge of widespread, due to the increased interest in more flexible production means and improvements of the quality of ergonomics. Exoskeleton technology can revitalize the manufacturing and logistic workplaces, impelling further developments of the efficiency of the human worker and overall safeness of the workplace that is required, but given the lack of regulations a series of challenges for the workers' health and economic risks for the employer are occurring.

A valid example for the implementation and regulation in the operational filed is the model of Toyota's Woodstock Plant which made the upper body passive exoskeleton AIRFRAIM©, from Levitate Technology INC, mandatory as protective equipment [6]. As exoskeletons are implemented in large companies, it is expected that these devices will be implemented further in industry as protective equipment. The scientific background and studies for the objective validation of these devices have been made with electromyography (EMG) sensors [7]. This step represents a milestone in the further integration of the devices in the operational environment and the establishment of the technology in the industrial domain as a protective and preventive measure for professional disorders.

2.3. Digital human models for ergonomics improvement

To increase the workplace safety and avoid work-related musculoskeletal problems, it is therefore mandatory to analyze physical risk factors [8]. Using digital human models, the ergonomic evaluation of the workplace is realized [9]. The end result for the simulation industry is a large variety of libraries, pre-defined objects, motions, and analysis methods that are now available in the digital environment. Such features accommodate even the behavior of human body, with software such as Dassault Systems Delmia©, AnyBody Technology© or Siemens Classic Jack©. The scientific team uses the Siemens Tecnomatix software, the program portfolio being capable of process simulating using Process Simulate and for ergonomics simulation and study using Classic Jack. The concept of Digital Twin reproduces the reality with a better resolution, increasing the details of the renderings, starting from the form and design and all the way to mechanical, electronic, and discrete events. Therefore, the exoskeleton models can be coupled and mounted on the digital human, enabling the use of Digital Twin [10] as a tool to integrate the device.

3. Hybrid worker Digital model current status and evolution

The human digital models that are available on market provide ergonomic analysis tools which are useful for the process planners but are lacking the tools needed for the close interaction of the exoskeletons and humans. There are some tools that add to the possibility of close discrete interaction (such as the "Force solver" in Siemens – Jack) but the capabilities are limited to forces applied to the humanoid body, lacking the torque and pressure points which might appear in such conditions. The concept design of the coupling includes the available tool in a pre-applied manner, the humanoid and the exoskeleton are coupled together while the forces are applied as external interactions on the body.

3.1. Coupling of human and Exoskeleton digital models' methodology

The schema in Fig. 1. depicts the development of the human-Exoskeleton coupling technique. The main process is composed of four steps: 1) The Coupling (Direct interaction of the humanoid with the exoskeleton) – where the dark green describes the first digital coupling [11] while the second one represents the updated version with the "Force solver" inclusion; 2) the Simulation (the extended digitalization which integrates the hybrid worker in the workplace) – in green representing the original simulations which have at the core the ergonomic tools from Jack by Siemens, and the yellow for the enhanced simulation – adapted from the EMG [11] data and motion capture. The association of these experimental and digital studies is represented with the blue color and is the third step –3) Analysis in this field the key process factors are collected. The end results are integrated further on in the future coupling for the 4) Optimization process of the Digital Twin.

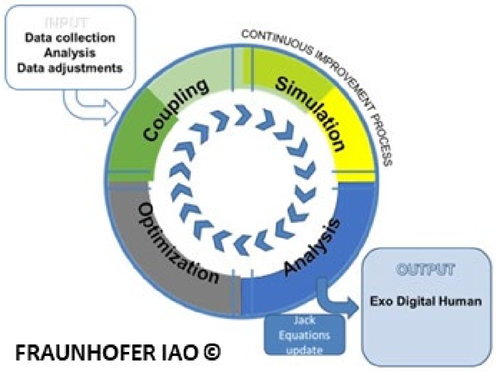

Fig. 1. Digitalization of the Operator 4.0 Methodology. Adapted from [10,11].

3.2. Experimental results and empiric data

The direct integration of exoskeletons implies the utilization of these devices in the operational field without a previous study or preparation. This method is effective as an experimental plan and can provide the most precise data and analyses since the interaction can be directly measured and collate with the manufacturer's specifications and the unmediated form of the workplace layout.

Fig. 2. Electromyographic study of the lower back - Erector spine at the workplace level (left), Motion capture using Xsens technology (right)

The main method used for the validation of exoskeletons in the operational model is the electromyography sensors data acquisition [10], this method having the advantage of unconcealed verification of the affected body region (e.g., Fig. 2. - Erector spine for lower back exoskeleton devices). Another way to determine the modifications of parameters of the motions at the human body level is through the motion capture analysis, the Xsens system provides graphical analysis of the data which reveal a difference between the natural movement of the worker and the motion while using an active Exoskeleton. In order to identify the KPI's (key performance indicators) for ergonomic evaluations the group conducted a series of experiments analyzing the motions in the sagittal plane.

The main motions analyzed during the experiments can be divided in three elementary operations: lifting, holding, and lowering. These are the elementary movements of a worker in a wide variety of workplaces. The activity represents the chain of elementary operations soldered together and the scenario is a cumulative activity (for e.g. the worker's shift). The available hardware technology used in the experiments is an active commercial exoskeleton for the support of lower back and the motion capturing suit from Xsens [12]. For the software systems, the group used Siemens Classic Jack and Siemens Process Simulate for modelling and simulation and MVN Analyze from Xsens for the motion capturing data. MVN Analyze uses the principles of inertial sensors, bio-mechanical models, and sensor fusion algorithms to become a full-body human measurement [12]. The L5 body segment and the CoM (center of mass) was later analyzed by using this software (e.g. Fig. 3.). The exoskeleton used is equipped with an UI (user interface) were different configurations of the support force (0-100%) and adjustments of the Reactive force (0-100), Sensitivity of the device (0-100) and Counter force setup (0-100) can be set, are as follows: the support 100% while the sub-settings are the sensitivity 10, the reaction 5 and the contra force 0. The experiments were concluded in multiple sessions of lifting, lowering, and holding heavy goods (from 0 to 30 kg) with and without the exoskeleton. Starting from the first session with 0 kg and increasing each session with 5 kg. The analyzed technical parameters such as position, velocities, accelerations, joint angles, and the trajectories of the centers of mass give a better understanding on the effects of the strains on the L5 joint segment of the worker.

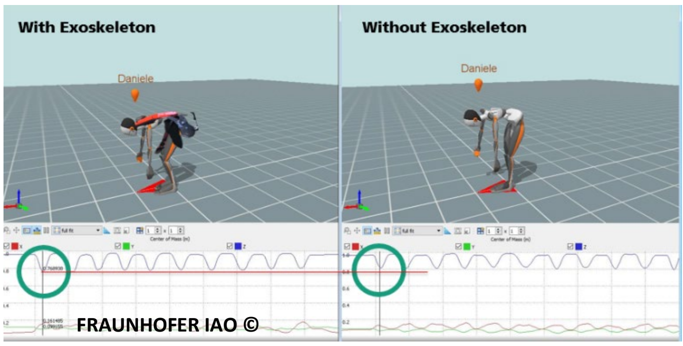

Fig. 3. Position of the CoM - Lifting Sagittal plane (z axis motion)

The motion-captured data reveals a peak in the lowering and lifting process, as the Center of Mass of the subject has been modified by the weight of the Exoskeleton and the activity behavior of the worker, effect that might occur because of the torque of the motors from the Exoskeleton, which accelerates the lifting.

The resulted data is referring mainly to the directly affected body area – the lower back L4/L5 vertebras and the muscular erector spine, further research is necessary on other body areas such as legs and shoulders, given that these are under the effect indirectly. These in detail studies, performed in experimental set-up provides the empiric background for the implementation in the digital environment.

The gathered data is the foundation for the future of the implementation of Exoskeleton technology in the Digital Twin model and will facilitate the integrations of such technologies in the industrial environment.

3.3. Digital Exoskeleton-based workplace ergonomics

As central part of the methodology, the coupling is constantly improved based on the data provided within the experimental beds, these processes identify the KPI`s for the ergonomic measurements of the Exoskeleton. Furthermore, the resulted coupling is animated to the tasks of the studied workplace, and the resulted ergonomic parameters are interpreted with consideration to the inclusion of Exoskeletons, in this case the strain on the lower back is reduced accordingly EMG data.

Initially, to decrease the strain on the lower back, alteration of the total load is taken into consideration. The disadvantage of this method is the broad decrease of the load at the level of all the kinematics joints of the humanoid model, affecting the simulation globally.

To recreate the digitalization of the workplace measurements from the site are used, while the tasks and motions are recreated from video evidence. This process is possible with the input data from the supposed employer of the exoskeleton, the process being filmed, the layout of the workstation photographed and measured for the realization of the digital environment. The video-proof has the goal of revealing the motions and activities needed within the work task. This way the workplace documentation can be detailed, and the data can be used for the process of digitalization. After the workplace documentation the digital transformation can begin, with the layout of the workplace and the motions and trajectories of the human the ergonomic analysis of the task can be realized.

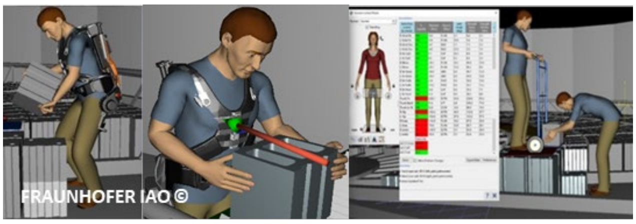

Fig. 4. Digitalized workplace task with an active commercial exoskeleton (left), Ergonomic analysis tools (Force Solver)– Jack Siemens (right).

The ergonomic assessment tools available and used from Siemens Classic Jack are: Force Solver (Figure 5 right), NIOSH, OWAS, RULA analysis method, can be used to analyze any workplace from the fatigue and effort perspective.

The data obtained from the motion capture, such as the variation of the CoM or segment motion deviations are useful in the calculation of the direction and orientation of the forces in the “Force solver” tool, the applied forces provide direct feedback in the ergonomic assessment tools.

As the initial coupling was only a visual one, based on the traditional biomechanical models [13] forces and supports from Force Solver were created and applied on Jack model.

4. Conclusions and further work

With all the above, the digitalization of the hybrid worker is still in an early stage, the state of the technology and the lack of standardization for industrial Exoskeletons represents an impediment for the market to grow and for the process planners to implement these devices.

The development of a digital tool for the integration of Exoskeletons in the working environment is mandatory for the industry. The transformation of a generic hybrid Human/Exoskeleton digital model towards the integration into the workplace consists of a well-planned method which has the potential to integrate the devices in the workplace with low costs and with the benefit of ergonomic analysis tools.

By taking into the account the importance of the workplace ergonomics a series of analysis and experiments were done on the transformation for the final product to be acceptable in the industry. From the experiment’s empiric data was gathered and implemented for a better understanding of the process.

Further step in the development of the method will be by integrating a more concise study of the biomechanics of the human digital worker using software such as Math Lab and Anybody. The presented method is the foundation for future ergonomic analysis tools for the direct interaction of human with the Exoskeleton, the novelty and industry advantage in this technic consists of the simplicity of the direct analysis, avoiding implications of biomechanical knowledge. This has the potential to push forward the technology to the process planning and furthermore into the shop floor and production.

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