Towards an Approach for a Holistic Ergonomic Work Design Using Physical and Cognitive Digital Human Models

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Abstract. Digital human models enable an economic and ergonomic design of products and work processes. These models investigate different aspects of the human. Anthropometric and biomechanical human models depict the physical characteristic and are used to examined physical load regarding feasibility and tolerability and in some extent to economic efficiency. Cognitive human models can model task knowledge, expectation driven behavior, learning as well as the impact of restricted resource such as attention and working memory. Only few approaches include cognitive as well as physical aspects at the same time due to complexity of the approaches and different scientific communities. Bringing both fields together will enable a holistic ergonomic work design by including physical and cognitive skills. Based on two use cases from product and production ergonomics, it will be shown (1) how the combination of both model forms can result in ergonomic evaluation (2) what information is needed to flow between model approaches for integration purposes. That will be shown by using a cognitive (cognitive architecture ACT-R) and two anthropometric models (ema Work Designer, RAMSIS). Finally, the potentials of holistic model approaches for the future and the challenges that must be overcome will be discussed.

Keywords: Cognitive model · Ability-appropriate Work Design · Digital Ergonomic · Holistic Ergonomic Approach · Digital Human Model

1 Multiple Usage of Digital Human Models

Work situations are becoming increasingly complex and multifaceted. Be it in the operation of machines or the interaction with machines and people in work processes. There are multiple interactions and dependencies between the elements of the environment, the

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objects in the environment, the physical actions per-formed and the cognitive processes necessary to perform the task. The flexibilization of work and man-machine communication already played an essential role in the research field 'Industry 4.0'. In the following generation of production systems 'Industry 5.0', the flexible handling of the working person to dynamic work situations that vary at any time is a central content. The resulting requirements from a more complex and more dynamic working environment for evaluating work situations demand better and more holistic digital human models. These holistic digital human models should take into account how changes in environment configuration, availability of information and temporal dependencies have an impact on the physical and cognitive demands of a working situation.

So far digital human models of physical aspects and cognitive human models are developed and used in different research and application fields (Paul 2021). It is time to find ways to bring these approaches together.

2 Physical and Cognitive Digital Human Models

2.1 Physical Human Models: Anthropometric and Biomechanical Digital Human Models

Physical digital human models make a significant contribution to placing people at the center of consideration in product and process development as early as the planning phase (Paul 2021). Digital human models in general enable an economic and ergonomic (cognitive and physical) design of products and work processes. These models investigate different aspects of the human Bullinger & Hoffmann (2016). These approaches usually concentrate on anthropometric digital human models which describe the mechanical properties and functions of the human body. Anthropometric depict the physical characteristics and are used to examine physical load regarding feasibility and tolerability and to some extent to economic efficiency. Digital human models such as ema Work Designer (emaWD), Human Builder, Jack, RAMSIS enables the creation of the workplace and the simulation of work processes. Digital human models can be significantly adapted in terms of anthropometrics and physical information (e.g., gender, body height percentiles, flexibility, force) regarding nationality or age groups and can therefore be used for ability-based work design. Different methods can be used to generate the movement e.g., key frame methods, motion capturing, model-driven models and to analyze the work process e.g., visibility, accessibility, posture, load or execution time analyses (Paul 2021, Spitzhirn et al. 2022b, Zhu et al. 2019).

2.2 First Extension of Physical DHM with Cognitive Analysis

In order to meet the high importance of visual conditions for the driver's place design, additional functions for the simulation of human perception, i.e. the first step in the cognition process, have been developed and added to the human model system since 2006 in the 'RAMSIS cognitive' project (Remlinger and Bengler 2016). These functions include the modeling of optical-geometric properties of stimulus-inducing signals from the driver's environment as well as the analytical simulation of optical-physiological properties of the human eye. Specifically, these are analysis functions for fields of vision, fields of view and spectacle vision. But attention allocation and information encoding which is necessary for informed decision making or goal directed visual search for specific information is not possible.

2.3 Cognitive Models of Human Behavior

Visual attention allocation and generating contextual meaning of perceive information for decision making can be well predicted with cognitive human models. These models focus on the cognitive processes that lead to the perception of information, information processing and action decision. Especially regarding the combination of different cognitive functions, cognitive architectures are interesting for dynamic work environment, since they try to implement the approach of the Unified Theories of Cognition (Newell 1994). According to this, cognitive functions can explain human behavior only through integration of different information processing units. One of the most used architectures is ACT-R (Anderson et al. 2004). ACT-R has an interesting structure since it has modules that hold specific processing units such as visual processing or auditory processing. The processed information is available in the respective buffers and depending on available buffer information a matching production fires that changes buffer content and triggers module activity e.g., such as looking for a specific visual object or retrieve specific representation (chunk) from declarative memory. The motor actions are quite restricted so far – key presses on keyboard or mouse can be used. This structure enables the cognitive system to show emergent and flexible behavior depending on the events external and internal states. This is interesting for tracing the cognitive state of operators in applied settings. Klaproth et al. (2020) showed an example of an anticipation model of a pilot especially in alarm situations. Scharfe-Scherf et al. (2022) shows predictions of take over times in highly automated driving depending on the complexity of the situation and the type of action decision to be made. But still cognitive architectures do not have a body and cannot perform complex movements.

2.4 First Extensions of Cognitive Models to Physical Interactions

One approach to add a sensorimotor control layer to a cognitive architecture has been proposed by (Karl et al. 2021). The authors developed an approach that combines a cognitive level (in ACT-R) with a sensorimotor level (Bayesian approach) to enable an agent to drive a rocket in a virtual environment with obstacles and to cope with unpredictable events such as drift and returns a sense of control depending on expectations of movement outcome. This would be far too fine tuned for digital human models and still does not enable complex movements of a digital body. There have been approaches to make ACT-R drive a car in a virtual environment and combine this with a model for interacting with different User Interfaces. This approach returns predictions of the distortions of driving behavior accordingly (Salvucci, 2009). Scharfe-Scherf et al. (2022) developed a flexible task model of a car driver that anticipated gaze behavior and can predict the time a driver needs to make a safe decision in taking over from automated driving to manual drifting according to the complexity of the situation. But still, a digital body with motoric capabilities and different perspective of visual information would be very interesting for foundational and applied research.

3 Using Physical and Cognitive Digital Human Models

3.1 Use Case: Machine Operation Center and Related Work Activities

The potential of a holistic human model systems is presented by an example scenario showing what is possible and where potentials lay regarding evaluating work activities.

The work task consists of the processing of supplier parts including the control of the orders and the creation of the machining program. The employee must independently **decide** on the necessary processing programs to be used and **set relevant parameters depending** on order which varies in sizes and complexity. The person also must conduct tasks which includes **selecting** and equipping the blanks, **monitoring** the machine, with partially **completing maintenance tasks**. In addition, a random sample-based quality control and a **final order confirmation** must be carried out. Depending on the order and the associated processing steps, the processing time varies from 30 s to 5 min. This results in **waiting times** for the employees, which can be **filled with secondary tasks**. The material is provided by forklift. The necessary information about the product to be provided and transported away is provided electronically. The machine operator provides support if necessary. **Potential dangers** must also be **recognized** and avoided at an early stage of development. When carrying out the activities, **various errors** such as dropping objects, incorrect processing programming or forgetting work processes, quality control documentation can occur that can lead to material damage or personal injury. Figure 1 shows an overview about the use case and related work activities.

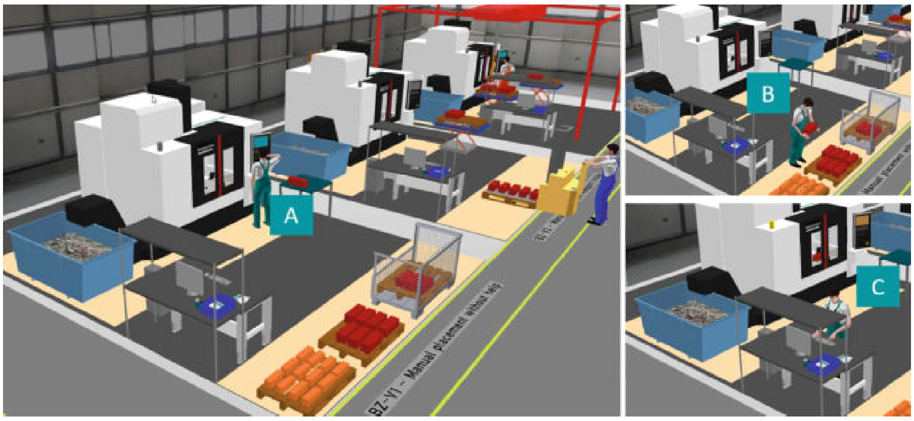


Fig. 1. Machine operation center with related work tasks (A: machine programming, B: material transport; C: quality control); displayed by ema Work Designer.

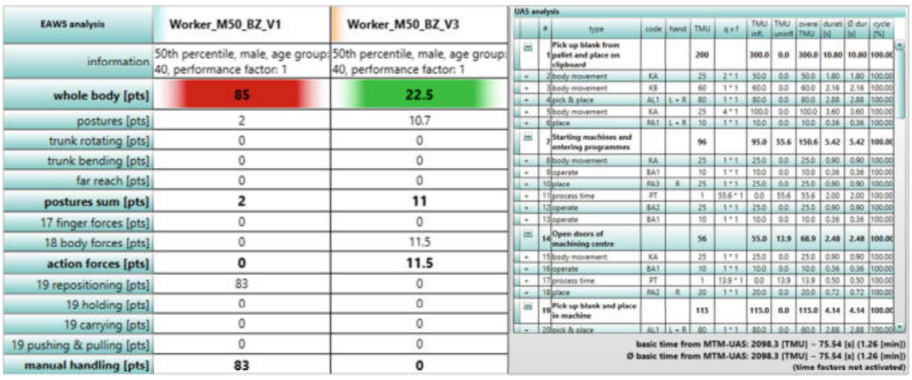
A forklift driver is responsible to load and unload, transport and store goods and materials. To fulfill these tasks, she must **adjust the vehicle** to her physical conditions to ensure **optimal visibility** and operation. This includes adjusting the mirrors, seat, and backrest. She also must **ensure the visibility** of all relevant areas around the vehicle.

All bold marked terms are example aspects that could be addressed by a holistic approach that combines cognitive and physical characteristics of the scenario.

3.2 Analyzing of the Use Case Using Physical Human Models

The two physical DHM ema Work designer (emaWD) and RAMSIS are used to analyze the machine operation center with related work tasks and the used forklift related to ergonomic and economic aspects.

emaWD enables holistic prospective planning, evaluation, 3D simulation and visualization of human work in the context of the Digital Factory (Fritzsche et al. 2019; Spitzhirn et al. 2022a). For the creation of the work process an extensive CAD library (e.g., robots, work stations) as well as import interfaces for CAD data, layouts or work descriptions can be provided. Humans can be fitted using an anthropometric human model with respect to gender-specific body sizes (P05, P50, P95, individual) and other performance characteristics such as age factors, flexibility, force. Based on the ema task library, the work processes can be simulated using a parameterized task description under specification of basic conditions (e.g., objects to be handled, target position). Different movement executions (e.g., bending instead of stooping) can be defined and the work process is automatically simulated in the emaWD. During the simulation, it is checked whether the process can be carried out. For the evaluation of the work process, different analysis methods can be used, e.g., standard execution time according to MTM-UAS, walking distances, as well as ergonomics risk assessment according to EAWS (Schaub et al. 2013) and NIOSH lifting index. Figure 2 (left) shows ergonomic risk score for current and optimized machine operation tasks based on EAWS. The introducing of handling device and the redesign of material supply reduce the risk score from 85 (high risk) to 22.5 (low risk). The execution time could also be decreased by 6,8 s to 75.54s per cycle (cp. Figure 2 right).



EAWS analysis	Worker_M50_BZ_V1	Worker_M50_BZ_V3
information	50th percentile, male, age group: 40, performance factor: 1	50th percentile, male, age group: 40, performance factor: 1
whole body [pts]	**85**	**22.5**
postures [pts]	2	10.7
trunk rotating [pts]	0	0
trunk bending [pts]	0	0
far reach [pts]	0	0
postures sum [pts]	**2**	**11**
17 finger forces [pts]	0	0
18 body forces [pts]	0	11.5
action forces [pts]	**0**	**11.5**
19 repositioning [pts]	83	0
19 holding [pts]	0	0
19 carrying [pts]	0	0
19 pushing & pulling [pts]	0	0
manual handling [pts]	**83**	**0**

UAS analysis

#	type	code	hand	TMU	q × f	TMU infl.	TMU uninfl	overall TMU	durati [s]	Ø dur [s]	cycle [%]
1	**Pick up blank from pallet and place on clipboard**			**200**		**300.0**	**0.0**	**300.0**	**10.80**	**10.80**	**100.00**
2	body movement	KA		25	2 * 1	50.0	0.0	50.0	1.80	1.80	100.00
3	body movement	KB		60	1 * 1	60.0	0.0	60.0	2.16	2.16	100.00
4	pick & place	AL1	L + R	80	1 * 1	80.0	0.0	80.0	2.88	2.88	100.00
5	body movement	KA		25	4 * 1	100.0	0.0	100.0	3.60	3.60	100.00
6	place	PA1	L + R	10	1 * 1	10.0	0.0	10.0	0.36	0.36	100.00
7	**Starting machines and entering programmes**			**96**		**95.0**	**55.6**	**150.6**	**5.42**	**5.42**	**100.00**
8	body movement	KA		25	1 * 1	25.0	0.0	25.0	0.90	0.90	100.00
9	operate	BA1		10	1 * 1	10.0	0.0	10.0	0.36	0.36	100.00
10	place	PA3	R	25	1 * 1	25.0	0.0	25.0	0.90	0.90	100.00
11	process time	PT		1	55.6 * 1	0.0	55.6	55.6	2.00	2.00	100.00
12	operate	BA2		25	1 * 1	25.0	0.0	25.0	0.90	0.90	100.00
13	operate	BA1		10	1 * 1	10.0	0.0	10.0	0.36	0.36	100.00
14	**Open doors of machining centre**			**56**		**55.0**	**13.9**	**68.9**	**2.48**	**2.48**	**100.00**
15	body movement	KA		25	1 * 1	25.0	0.0	25.0	0.90	0.90	100.00
16	operate	BA1		10	1 * 1	10.0	0.0	10.0	0.36	0.36	100.00
17	process time	PT		1	13.9 * 1	0.0	13.9	13.9	0.50	0.50	100.00
18	place	PA2	R	20	1 * 1	20.0	0.0	20.0	0.72	0.72	100.00
19	**Pick up blank and place in machine**			**115**		**115.0**	**0.0**	**115.0**	**4.14**	**4.14**	**100.00**
20	pick & place	AL1	L + R	80	1 * 1	80.0	0.0	80.0	2.88	2.88	100.00

basic time from MTM-UAS: 2098.3 [TMU] ~ 75.54 [s] (1.26 [min])
Ø basic time from MTM-UAS: 2098.3 [TMU] ~ 75.54 [s] (1.26 [min])
(time factors not activated)

Fig. 2. EAWS ergonomic score (left) and standard execution time based on MTM-UAS (right) using DHM ema Work Designer

The human model RAMSIS is focused on the application in the field of vehicle design and has very extensive anthropometric databases and functions for vehicle design. When used for the optimized design of products, especially vehicles and aircrafts, the focus is often on the consideration of minimal spatial conditions and the resulting complications for comfortable and safe use in a nearly static situation. The main factors influencing the simulation of the posture of the driver of a motor vehicle, or a mobile machine are the visibility conditions at the driver's position. With DHM RAMSIS the forklift can analyze related to the adaptability of the vehicle to the body dimensions and posture of the driver, the examination of the reachability and readability of the controls and displays as well as the visibility of the load and the environment as well as the examination of the reachability of the controls and displays. Using the ema Work Designer, the design of the forklift can also be evaluated regarding vision and reachability. Furthermore, the drive with the forklift and interaction with the machine operator can be simulated and potential risk situations can be identified and optimized (cp. Figure 3).

Fig. 3. Left: Vehicle design with DHM RAMSIS using visibility and accessibility analyzes; right: Simulation of a forklift and the interaction of driver and machine operator by ema Work Designer.

3.3 Analyzing of the Use Case Using Cognitive Human Models

With cognitive architectures flexible task models can be generated that flexibly react to events such as an alarm indicating a new task or necessity to change to another task. Possible errors in interacting with interfaces or visual search times for specific information in the visual field can be predicted. In Scharfe-Scherf et al. (2022), the flexible task execution depending on relevant object configuration and subsequent decisions can be predicted and correlated with reaction times of participant behavior.

Furthermore, the time needed to interact with a specific display to achieve a specific goal and how disruptions interfere can be predicted in such a scenario (Prezenski et al. 2017 and Wirzberger et al., 2015). The models can provide support in understanding and predicting influence of visual information configuration on task-time. Also, dangerous situations and potentials for mistakes can be evaluated and solutions developed and easily tested with the same model (since it is flexible). So far, cognitive models do not have a body and do not interact as an acting body with a complex dynamic environment. Therefore, also the visibility of objects depending on the body posture and occlusions are cannot be modeled or considered in a running model.

4 Benefit of Combination of Physical and Cognitive Systems

A big challenge is to build approaches that are flexible enough to react to changing situations and variations of a task. This could be a different environmental situation such as different object configurations the digital model needs to interact with. Also varying locations of visual information will change the performance of the task. Another source of performance differences are variations on a temporal scale such as bottom-up information like alarms that make it necessary to immediately switch to another task or change the sequence of actions. The sequence of steps in the task can vary depending on the availability of work pieces but also on the individual.

In dynamic situations such as the arrival of new material by forklift or interacting with a robotic system, people have specific expectations to be prepared in time on what will happen next and where to find relevant information. This use case illustrates how the worker and the forklift driver need to be informed in time about the material arrival, location, and tasks. For decision making, they also need to gather relevant information from the environment, such as displays, tools, or process states. These processes are essential for the evaluation and efficiency of a working process and might be delayed or disrupted if some information is not available.

Collaborative robots are a recent example of such external influences on the human working environment. They are more versatile as established assembly lines. These robots act more context based rather than time based as older working environments. This leads to a constant flow of information between the robot and the worker. Evaluating such work situations therefor require flexible and content-based evaluation tools. In the described use case, the worker informs the robot of the required task, and the robot gives feedback on task progress and quality. This information is shared with the forklift driver and the intra logistics. Performance in a highly dynamic multi agent system with different disturbance sources needs to be predicted by such a holistic DHM.

5 Intersection for a Holistic Human Model Approach

To enable a holistic approach to address flexible scenarios with the describe information processing capabilities we propose a general structure with specific interfaces between physical and cognitive human models for a holistic human model approach that incorporates both physical and cognitive attributes. This structure should be feasible and scalable for different purposes. We demonstrate how this structure can be implemented by integrating a specific cognitive architecture (ACT-R) and two anthropometric digital human models (emaWD and RAMSIS). We show the benefits of this integration and the requirements for the two model approaches. The general structure can be applied to other cognitive models and digital human models. The cognitive human model (see Fig. 4) receives input from the perception capabilities of the digital human model through an interface. This input data is used for information processing and decision making. The cognitive model sends commands to the posture and movement control of the digital human model through another interface. This enables the execution of motor actions.

The cognitive model can initiate attention allocation processes on the visible objects that depend on the model's posture, such as focusing on a specific object or reading specific words. The "vision" structure of ACT-R contains a list of visual objects that can be attended at this moment, with attributes such as location, distance, identity, color and more. The model can perform a visual search on these objects based on the goal and the relevance of locations or a specific color. The attended object will be encoded and available in the buffer (dashed box) for further processing. The list of available objects changes when the physical manikin moves, so the perception module is partly influenced by the physical DHM and partly by the cognitive approach that can guide attention. The cognitive human model can also transfer an action decision to the DHM.

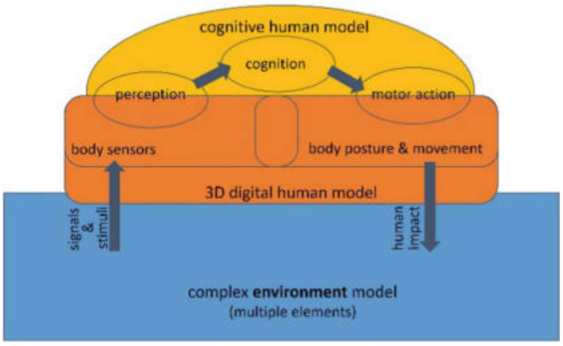


Fig. 4. Structure of the information process of a holistic digital human model

In the geometric environment of a CAD model of a production site, a RAMSIS or emaWD manikin is positioned in work environment or a driver's place environment of, for example, a forklift. To determine and subsequently simulate activity of the forklift driver, the manikin would have to decide whether the object in front of it is a pallet with goods that the forklift would have to pick up or an obstacle that it would have to drive around with the forklift. The CAD objects that have now been captured and their relative positions analyzed should each be labelled in the system. This means that some semantic properties are stored for the geometric objects. These could be, for example, the name, function, size, shape and color of the object just as necessary e.g., by the list of objects and attributes required by an architecture such ACT-R. These semantic properties can be transferred to the cognitive model via a data interface and be available there as input data for attention allocation and subsequent decision-making process.

6 Summary and Conclusion

In this paper the necessity of an integration of physical digital models with cognitive digital models towards a holistic model is shown using the physical DHM-systems emaWD, RAMSIS and the cognitve model ACT-R. Different advantages are discussed such as adding flexibility to task execution in dynamic task settings and to have a lager range of evaluation possibilities. Furthermore, dynamic decision making as well as information design (visual and auditory) do have a strong impact on task execution time and on quality and risk assessment. For the integration of both model forms a general interface structure is developed that should be able to transfer visible objects to the cognitive models and action decisions to the digital human model. Next steps are to start with a smaller task for a first holistic digital human model to build a demonstrator. Depending on the specific purpose of the digital model the most relevant functionalities and cognitive processing modules will be chosen to enable a feasible approach.

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