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Methods to objectively ensure ergonomic standards in driver cabins

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This paper introduces a method for assessing the design of operating systems as part of cognitive ergonomics, as well as a method for assessing operator movements and gripping areas as part of physical ergonomics. Both methods can be used in the development of a cab or for comparative analysis of cabs. The innovative character of the methods is to establish a non-subject based evaluation process that provides more objective and comparable results across different examinations. The method of evaluating operating systems builds on the ergonomic principles of expectation conformity and movement compatibility. The motion capturing method for analyzing and evaluating gripping areas and movements uses the comfort angle specifications of the German Social Accident Insurance (DGUV).

Keywords

Ergonomics, operator workstation, evaluation, method, operating Systems, gripping areas, motion capturing

While many characteristics of agricultural machinery can be measured in numbers and thus objectively evaluated, the ergonomic evaluation of a driver's cab often has to be carried out by interviewing a sufficiently large and heterogeneous group of subjects (Kowalewsky 2014, Wilmer 2015, Ai et al. 2017). After trial sitting or prolonged use with the machine, subjects are asked about specific criteria. On the basis of the chosen group, an objectification of the subjective impressions and evaluations of the individual subjects is achieved to some extent. However, this type of objectification is not always expedient which is shown by a sound pressure measurement with a sound pressure level of at least 77 dB (A) at ear height, which was still rated as pleasant by the group of subjects (Wilmer 2012). Hence, it is not certain that even objectively measurable values can be correctly classified by subjects. This finding can be explained by the biopsychosocial model of pain, according to which pain or discomfort depends not only on biological, but also on psychological and social circumstances (Hohmann-Jeddi 2015). The proof is provided by Tiemann et al. (2015) in a study in which 20 subjects always received the same painful stimuli on the backs of their hands. Once without cream and once with supposedly pain-relieving cream. Because of their expectations, the subjects rated the same painful stimuli with applied, pharmacologically inactive cream significantly weaker and also the nerve cell signaling pattern differed in both cases. Based on the method presented here for evaluating the gripping areas, it can be derived that unpleasant movement or postures in the cabin may not be inconvenient for subjects if they expect it to be a pleasant movement or posture. This assumption speaks for an evaluation process without interviewing subjects. This also applies to the method used in the field of cognitive ergonomics: An operating system can be assessed more objectively and more equally across different examinations with regard to the design of the movement and actuation directions of control elements based on relevant literature.

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Theoretical basics

Figure 1 shows how the test contents and methods described later are classified in the overall context of human, workplace, work, and work environment. In the workplace, the human performs his or her work in a working environment. This results in physical and/or cognitive load for him or her. The working environment can cause noise, vibrations, climate, toxic substances, and lighting conditions as loads (Dupuis 1981). Everyone experiences the same load in a given workplace with a given work task. However, the stress on a person is individual and depends on their performance, state of health, and motivation. Load and stress are positively correlated, which is why a reduction in load also leads to a reduction in individual stress. Through training, health-promoting measures and employee motivation, it is possible to reduce the stress on a person with a given load. The task of the engineer and developer is to optimally adapt the loads to a person. It is not an absolute minimization of the two parameters pursued, but a load and stress optimum, so that the human is neither over nor under-challenged. The loads from the working environment are mainly quantifiable and verifiable by guidelines and standards. The work-related, non-directly measurable, physical and cognitive loads can be captured using the assessment methods presented below.

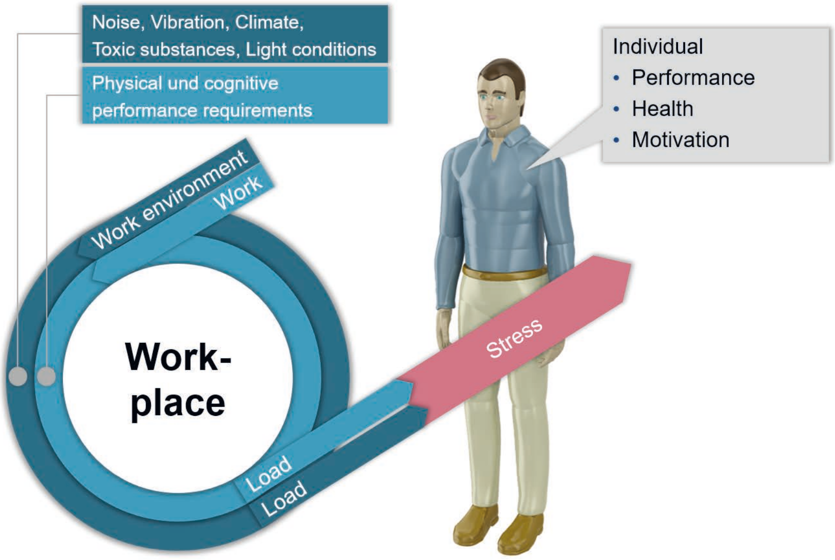


Figure 1: General basic scheme of the loads and stresses resulting from the workplace of the human according to Dupuis (1981)

A cabin for agricultural machinery must – building on Figure 1 – meet the following requirements; the contents of our test methods are marked in green (Figure 2):

- Accident safety – In the event of an accident, the cabin must adequately protect the driver against mechanical impact. At this point the security structures ROPS, FOPS, and OPS as well as restraint systems on seats can be mentioned. Exact requirements are described in an EU Regulation (EU 2016).
- Protection against influences from the working environment – The driver has to be protected against harmful or performance-reducing influences from the working environment. These are

in detail the climate, toxic substances, noise, vibrations, and the light conditions. Exact requirements are also described in an EU Regulation (EU 2016).
- Comfort – Facilities such as radio, cup holders, shelves etc. are part of the comfort.
- Workplace to perform the work task – The driver should be able to carry out all work tasks on his workplace in the cabin with adequate cognitive and physical load. The term load should initially be considered neutral, since a load in this case can have a positive, neutral or negative effect on the driver (DIN 2011a). Therefore, the optimal load should not be described as „small as possible“, but as „appropriate“.

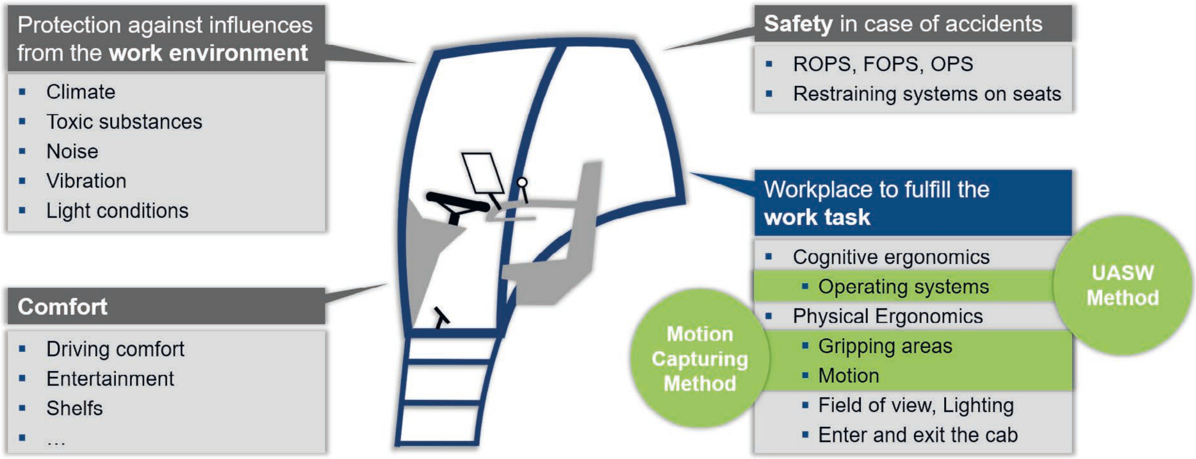


Figure 2: Main functional areas of a driver‘s cab and test contents covered by the methods (green)

UASW method for the evaluation of operating systems

Theoretical basics

According to Zühlke (2005), cognitive ergonomics include all mental processes for operating a system. The less an operator has to think about the operation, the more intuitive the operating system is designed. This is the case if already learned procedures for the operation of technical systems can be activated. For example, one stereotype is to turn a knob clockwise in anticipation of an increase in value and counterclockwise in anticipation of a decrease in value. The learned procedures raise expectations in the operator of how to operate controls and read displays. The procedures and expectations are generally valid for a wide range of operators or populations. This is why we speak of population stereotypes. The remarkable thing is that users fall back into these population stereotypes in stressful situations even if they have to act in the opposite way according to their education (DIN 2009). These population stereotypes should therefore play their part in the operation of machines so that they can be operated as intuitively as possible.

However, the knowledge about the functionality of a machine is to be distinguished from that. The operation of a machine can only be intuitive if the functionality of the machine is known before. The model in Figure 3 illustrates the relationships: In terms of functionality, individual products can always be assigned to a super-category. The knowledge about the functionality is brought along and extended across the categories to the individual product. In the field of mobile machines and especially for the tractor, the functionality required for achieving added value exceeds the primary driving task by far and is usually not intuitively, but only after instruction or self-study. A driver needs a certain amount of time to get to know it. This is the part-learning-time t_F for the functionality.

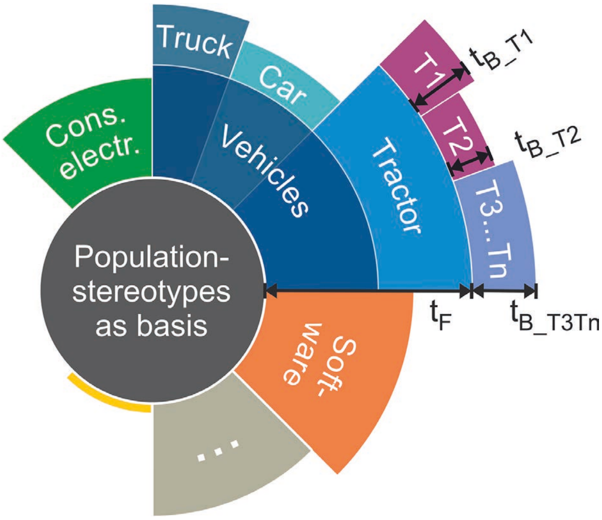


Figure 3: Model for describing the learning time as the sum of the part-learning-times t_F for the functionality and t_B for the operability; the intuitivity of an operating system is mainly based on the part-learning-time t_B for the operability

As soon as a driver is aware of the functional possibilities of a machine type, the design of the operating system determines how intuitive it is to use. That is described with the part-learning-time t_B for operability. For example, all standard tractors have mainly the same functionality, but undoubtedly differ in their operability from manufacturer to manufacturer. The functionality and operability can be summarized in the usability.

The decisive quality feature is the total learning time ($t_{Lsum} = t_F + t_B$) that a driver needs to use a machine as effectively, efficiently, and satisfactorily as possible according to the definition of usability (DIN 2011b). While the requirements for the functionality of a tractor are of a general nature, the design of the operating system in the development process is product-specific. For this reason, the focus is laid on the part-learning-time t_B for operability for the derivation of the first test method. The basis of the method is the following statement: The more the design of an operating system corresponds to the population stereotypes as the basis, the shorter the part-learning-time t_B and the more intuitive the operating system (DIN 2009). Although the tractors T1 and T2 in the example in Figure 3 have the same range of functions from the same manufacturer, the part-learning-time t_{BT2} is less than t_{BT1}. The operating system of T2 thus corresponds more to the population stereotype than that of T1. The manufacturer of T3 designs all operating systems the same, which is why the driver no longer has to spend any further learning time on all other tractors Tn. Furthermore, it is to be assumed that a longer learning time for operability causes a shorter half-life of knowledge about the learned operation.

For the stereotypical design of operating systems, Bullinger (1994) defines the concepts of expectation conformity and movement compatibility. By the expectation conformity and movement compatibility, the theoretical relationships of the basic elements user (U), display (A), control element (S), and active part (W) of a human-machine interface are described in the UASW model (Schmid 2003). This model is used as the basis of the evaluation method. Figure 4 shows the relationships related to our application: A machine has n functions and for every function k there is a relationship between user, display, control element, and active part. The sum of all displays A_k and control elements S_k is the operating system. The active part W_k causes the actual effect of a function k, for example a state change, value change or movement. The fulfillment of the expectation conformity between display, user, and control element as well as the movement compatibility between display, control element, and active part are the evaluation principles of the method.

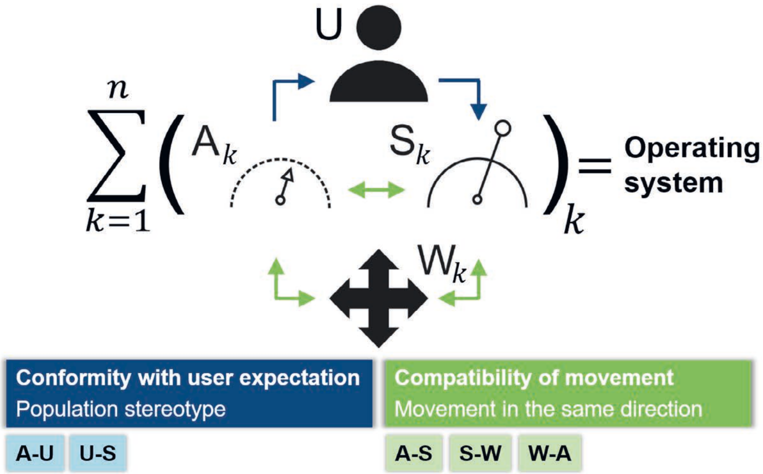


Figure 4: The UASW model and compatibility and conformity requirements for each element

Execution of the method

The method can be applied either to the UASW groups of all functions, to a functional collective, to a specific function or to functions that depict the most-frequent-case and the worst-case. Each UASW group is evaluated using the scheme shown in Table 1.

Table 1: Evaluation scheme for the UASW Method

Name of the function:			
Criterion	**Relation**	**Degree of fulfillment**	**Explanation**
expectation conformity	U – A		
	U – S		
movement compatibility	S – A		
	A – W		
	W – S		
	Σ_{err}		
	Σ_{max}	20	
	Operability factor (BF)	$\Sigma_{err}/\Sigma_{max}$	

The degree of fulfillment is determined by the scale according to VDI 2225-3 (VDI 1998). Figure 5 gives an example for the evaluation of the movement compatibility between active part W and various arrangements a, b, c of a control element S.

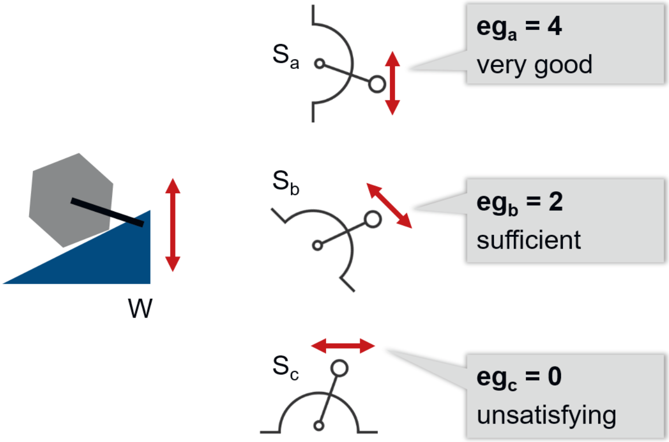


Figure 5: Example for the evaluation of movement compatibility; Active part W: header, control element S: height adjustment

The individual steps of the method can now be combined using an example from the operation of combine harvesters (Figure 6). First, use cases on the combine harvester are determined which are to be evaluated. For example, one or various most-frequent case(s) and one or various worst-case(s). In this case, „raise and lower header“ as the most-frequent case and „adjust bearing pressure of the header“ as the worst case.

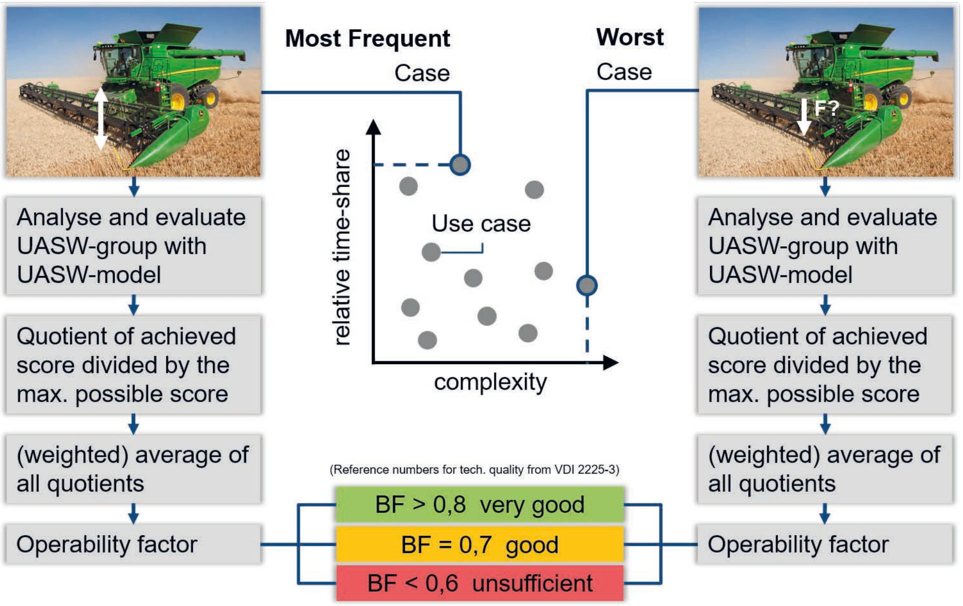


Figure 6: Holistic depiction of the UASW method

Then, for each function the UASW group is analyzed and rated using the UASW model and the template in Table 1. The quotients of the investigated UASW groups are at the same time the operability factors (BF) of the individual functions. The operability factors of individual functions can be summarized via a (weighted) average value to a total operability factor for a group of functions or for the entire operating system. The operating system can therefore be evaluated absolutely or in relation to others. In this way, the operating system can also be evaluated at an early stage of development or even without a prototype in the concept stage. Böttinger et al. (2011) showed the method for the first time when comparing the operating systems of three combine harvesters, Schempp and Böttinger (2015) presented a further developed and more detailed application for evaluating the operating systems of two tractors.

Basically, seven dialog principles can be used in the evaluation of operating systems (DIN 2008). In the context of the operating system of an agricultural machine and the test method described here, the consideration of the principles can be described as follows:

- Suitability for the task is provided by assuming that all functions for using the tractor are defined in the specifications and are basically operable.
- Self-descriptiveness is presumed because the haptic controls indicated by a symbol are accessible to the user at any time in the direct access.
- Conformity with user expectations is part of the test method.
- Suitability for learning is positively correlated with the adherence to expectations and movement conformity (Figure 4) and thus taken into account in the method.
- Controllability of a dialog is not taken into account, since during the actual operation of agricultural machines the execution of a software dialog plays a subordinate role.
- Error tolerance in the sense of error detection and correction suggestions is not taken into account. By contrast, the assessment and compliance with expectation and movement conformity aims to avoid operating errors.
- Suitability for individualization is not a criterion in this test method. Operating systems of agricultural machinery are customizable to a small extent only.

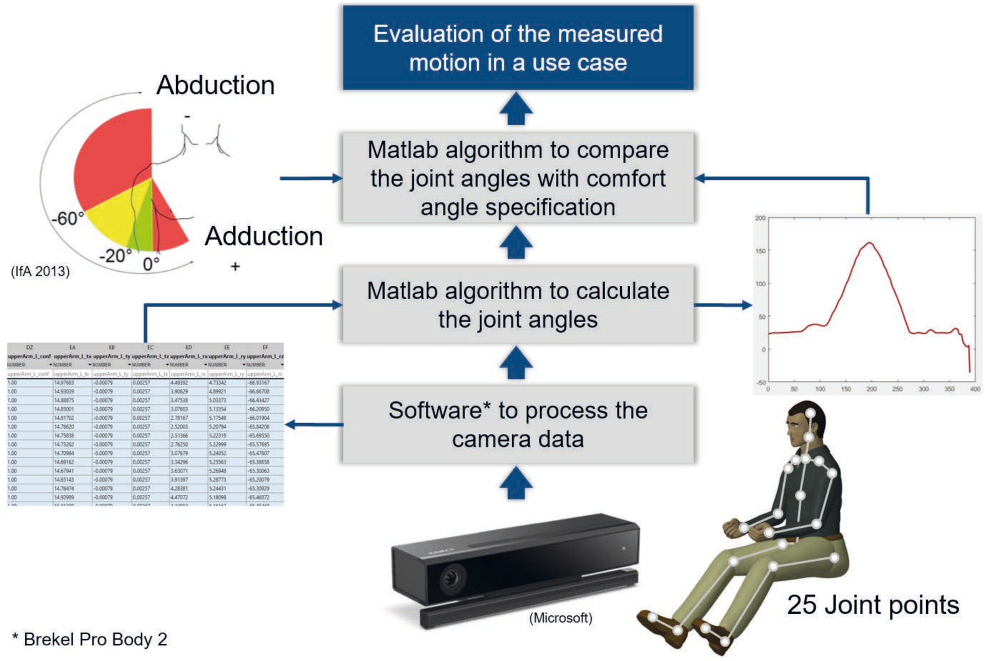
Motion capturing method for evaluating gripping spaces and movements

Theoretical basics of motion capturing and the measuring system

There are various methods for the digital and objective recording of postures and movements (Bubb et al. 2015). At this point the development and application of a markerless optical method will be described. Optical and markerless methods have the advantage that there is no need to place any sensors in the form of goniometers or markers on a subject. However, the disadvantage is the necessary optical accessibility to all joints and the slight variability of the measured distance of the joint points that leads to a varying length of the body elements in the measurement. The movement analysis uses the „Microsoft Kinect v2“ camera. The temporal and spatial accuracy of the Microsoft Kinect v2 in tracking body movements has been evaluated in scientific studies (Capecci et al., 2016). In terms of time accuracy, the Kinect v2 achieves comparable values with the reference system: the average deviation is 0.5 frames to 1.4 frames at a recording frequency of 30 fps (frames per second), depending on the application. Capecci et al. (2016) confirm the results of Xu et al. (2015) and Galna et al. (2014). The spatial accuracy was investigated by Capecci et al. (2016) based on postures and movements. Regarding the upper body, relative errors of 5.3% to 12.7% were determined during the movements. In the postures, the value of the root-mean-square deviation with respect to the distance of the elbows to each other was between 2.7 cm and 4.7 cm. Otte et al. (2016) rated the Kinect v2 with deviations of 1 cm to 2 cm from the reference system in the upper body area as a reliable tool suitable for clinical measurements. In particular, the anterior/posterior motion detection is rated as excellent, medial/lateral as good and only vertical as moderate to good. In all references, less good leg and foot accuracy is noted. For the case of use described here in the upper body area, the Kinect v2 can therefore be used as a suitable measuring instrument for data collection.

Execution of the motion capturing method

Figure 7 shows the steps of the method which are described below. First, an algorithm places a total of 25 joint points on the filmed subject and determines their positions in space at 30 fps. For each body element a local Cartesian coordinate system (COS_{xyz}) is calculated in a way that one coordinate axis lies in the longitudinal axis of the body element.



(IfA 2013)

(Microsoft)

* Brekel Pro Body 2

Figure 7: Motion capturing method based on a Kinect v2 camera

The location of a local COS_{xyz} of a body element is referenced to the local COS_{uvw} of the more proximal body element. The hip point is the top-most parent of the body element hierarchy of the whole body. The position is described by Euler‘s rotation angles which result from rotation of the local COS_{xyz} around the axes of the parent COS_{uvw} in the order u-axis, v-axis, and w-axis. The origin of a local COS_{xyz} of a body element is at the same time the distal end of the more proximal body element. The length of a considered body element is thus the magnitude of the vector between the two origins. Figure 8 shows the systematics of coordinate systems for the shoulder and elbow joint.

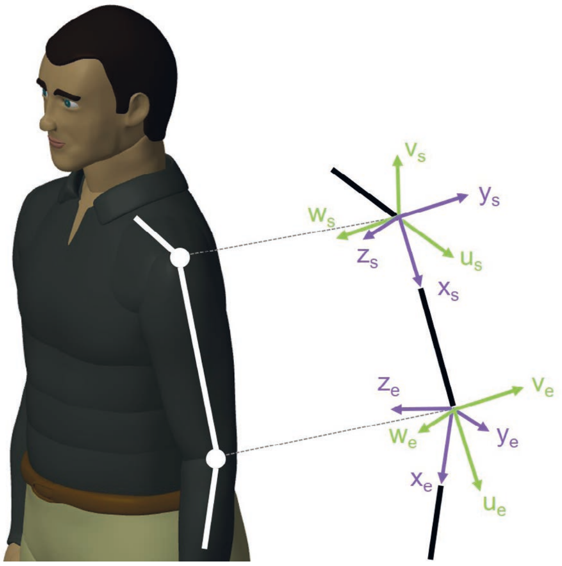


Figure 8: Systematics of the coordinate systems of the body elements using the shoulder joint (index s) and the elbow joint (index e) as examples

Using the example of the abduction and adduction of the shoulder joint in the frontal plane of the body, the calculation of the angle values integrated into the Matlab algorithm can be understood. The vector a_{xyz} describes the length and position of the upper arm and is defined according to Equation 1:

$$a_{xyz} = \begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} \quad \text{(Eq. 1)}$$

The rotation matrices R_u, R_v, and R_w describe the rotation of the local COS_{xyz} of the upper arm with the axes x_s, y_s, and z_s around the local COS_{uvw} of the shoulder with the axes u_s, v_s, and w_s. The coordinate transformation according to Equation 2 describes the vector $\mathrm{a}_{\mathrm{xyz}}$ in the local $\mathrm{COS}_{\mathrm{uvw}}$ of the shoulder with the axes u_s, v_s, and w_s:

$$a_{uvw} = R_w R_v R_u a_{xyz} \quad \text{(Eq. 2)}$$

By a following projection of the vector $\mathrm{a}_{\mathrm{uvw}}$ into the u_s-v_s-plane of the shoulder, the angle can be calculated, for example relative to the coordinate axis v_s and thus relative to the shoulder. The magnitude of the vector a_{xyz} is the length of the upper arm.

The movement analysis and evaluation

Figure 9 shows how the recorded movements can be visually analyzed in a first step. The graphs show the course of the joint angles for the right shoulder and elbow for a two-time execution of the use-case „steering wheel, joystick, side console, and back“. The two-time execution shows the repeating accuracy of the camera assuming that the subject moves as equal as possible.

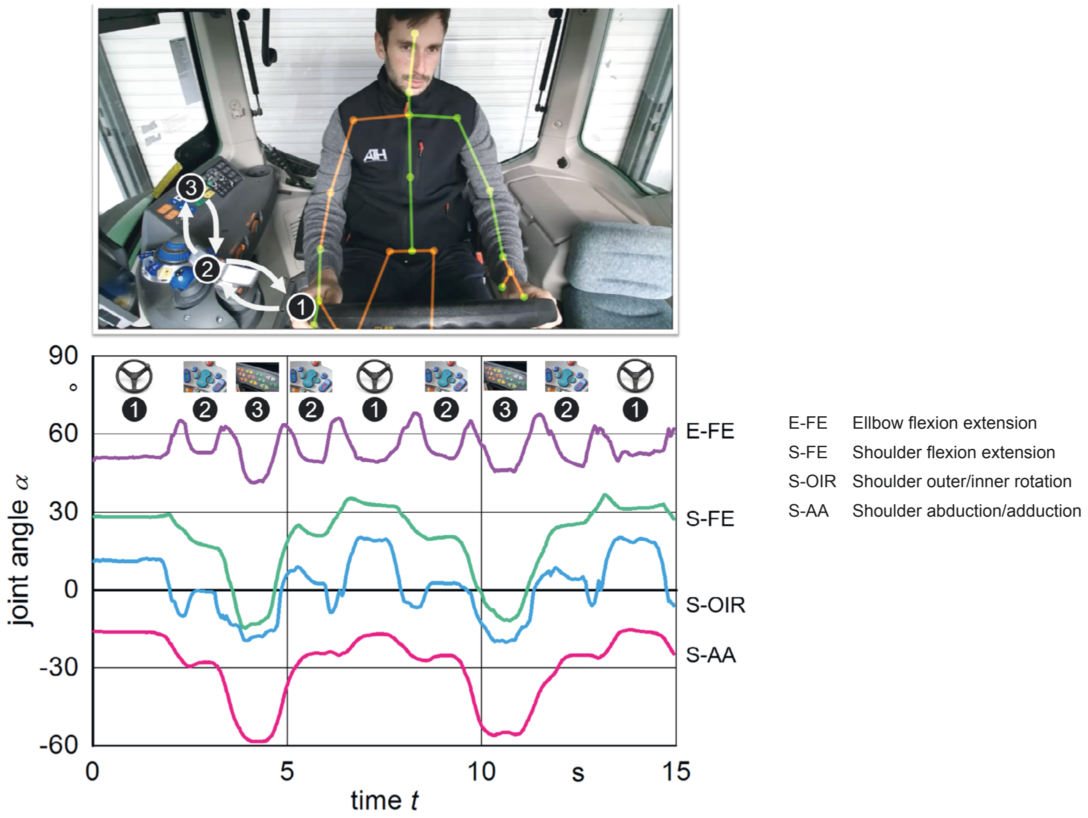


Figure 9: Joint angle courses for the right shoulder and elbow for a two-time execution of the use case “steering wheel, joystick, side console, and back”

In a further step, the movements are evaluated using a Matlab algorithm. The algorithm compares comfort angles from the literature with the calculated angle values (Figure 7). In our study, the traffic light system of the Institute for Occupational Safety of the German Social Accident Insurance (IFA 2015) is used. The evaluation is based on the three criteria green, yellow, and red (Figure 10). First, each joint angle value in each frame is assigned to one of the evaluation colors green, yellow, and red. The percentage distribution of colors for each joint angle across all frames allows to evaluate individual joint angles. For the evaluation of total body movement, the percentage values of the same color are summarized for all joint angles and divided by the considered number of joint angles. The classification system from VDI 2225-3 is used for the classification in which only the percentage value of the green color is considered: If the value of the green color is above 80%, the design of the gripping areas is good for the tested use case. If the value for the green color is between 60 and 80%, the design of the gripping areas is acceptable. At a value below 60%, the design of the gripping areas is unacceptable. In addition to the traffic light system, there are other posture assessment systems such as the „Rapid Upper Limb Assessment – RULA“ (IFA 2007).

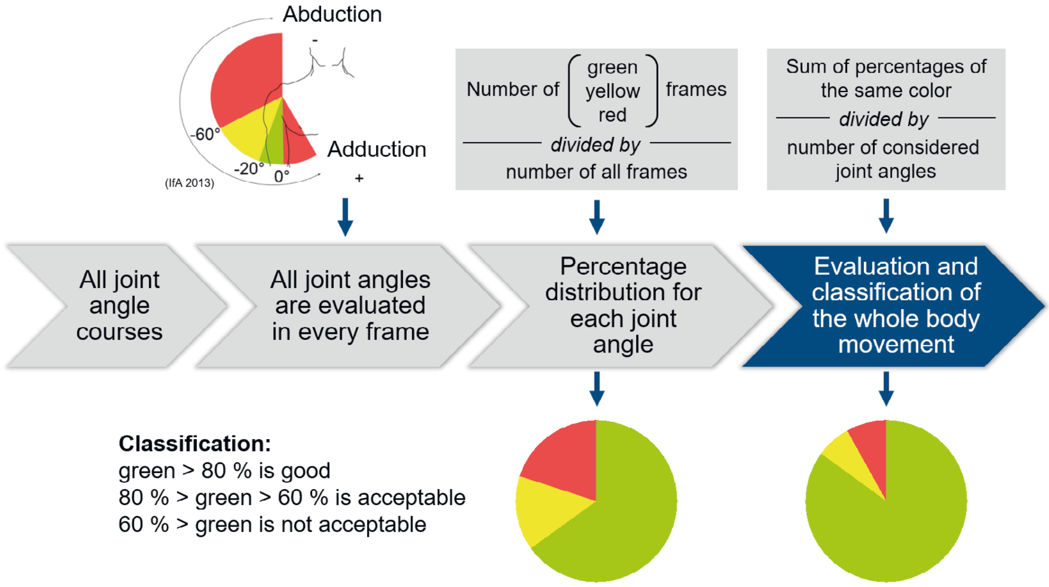


Figure 10: Concept for the integration of the traffic light system into the evaluation algorithm of the motion capturing method

Statistical investigation of the influences on the automated evaluation method

A study with 28 subjects (22 male, 6 female) and 17 use cases (7 postures and 10 movements) in the panoramic cabin of a Fendt Vario 313 was statistically evaluated (n = 476 observations). The subjects had to perform all use cases and rate them on a scale from 0% to 100%. The metric scale was associated with an ordinal scale where 0% was “unacceptable”, 60% was “acceptable”, 80% was “good”, and 100% was “very good”. This corresponds to the classification of the evaluation method described above. The statistical analysis was used to test the rating system for personal influences such as age, body height or gender. Also, whether the type of use case (posture or movement) has an influence. In addition, it was possible to check whether there is a correlation between the personal feeling of the subject and the result of the evaluation system. The null hypothesis of the statistical study is: The result of the rating system as a target variable is not influenced by the independent variables to be investigated. The following variables were recorded:

- The result of the rating system as a target variable
- The feeling of the subject as a continuous variable
- The gender of a subject as a categorical variable
- The age of a subject as a continuous variable
- The body height of a subject as a continuous variable
- The number of the subject as a categorical variable
- The use case number as a categorical variable
- The category of a use case (static/dynamic) as a categorical variable

The use cases were explained to all subjects in advance. Each subject was able to set the position of the seat and the steering wheel suitable for himself. The variation between the subjects and use cases was controlled by including the variables of the subject number and use case number as random effects in the model. This ensures that the correlation of the measurements for one subject across all use cases and the correlation of the measurements in one use case across all subjects is considered in the model. Namely, the model approach aims to evaluate the correlation within a use-case-subject combination. The categorical variables such as gender and category are defined as fixed effects. In addition, the covariates age, body height, and the feeling of the subject were included in the model. The interactions of the covariates with gender and category were also included in the model as a test, but only kept in the case of significance. Of the interaction effects, only the gender-specific perception of the subjects was significant. To capture random and fixed effects, a mixed linear model according to Equation 3 was used:

$$y = X\beta + Zu + \varepsilon \qquad \text{(Eq. 3)}$$

in which

- y is the n × 1 target variable vector for the result of the rating system,
- is the p × 1 vector of the fixed effects in the model,
- X is a n × p design matrix that assigns the fixed effects to the observations,
- u is the q × 1 vector for the random effects,
- Z is a n × q design matrix that maps the observations to the random effects, here the 28 subject number effects and the 17 use case number effects, and
- ε is the error vector of y.

The linear mixed model was adapted to the data of our study in the statistics program R (R Core Team 2018) with the lme4 package (Bates et al., 2015) using the maximum likelihood method. Fixed effects were tested for significance using the likelihood quotient test. Hence, the full model was tested against a model without the fixed effect in question. Age, body height, and category did not show any significance. The interaction of gender with feeling of the subject was significant (χ^2 (1) = 4.7, p = 0.0313). For the full model (equation 3), the residual plots did not show any noticeable deviations in terms of the assumptions variance homogeneity and normal distribution. The analysis of the model revealed a significant effect of the interaction between gender and feeling of the subject, with both gradients being negative. For women, the slope is significantly different from zero (-0.11 ± 0.034), but not for men (-0.02 ± 0.027). For the values of the covariates age (0.0004 ± 0.0004) and body height (-0.0005 ± 0.0009) no significant influence on the result of the evaluation system can be determined. On the basis of the confidence intervals, for the age difference (40 years) a maximum influence of -1.8% to +5.3% and for the body height difference (36 cm) a maximum influence of -8.7% to +4.7% on the results of the rating system can be determined. No difference was found for gender (score difference 1.7%; p = 0.372). Due to the small sample size of the female subjects, the quality was also calculated (Stroup 2002). For a score difference of 10%, the given sample size resulted in a quality of 80%. It can also be derived from the data that the variance of the use cases is about twice as large as the variance of the subjects.

Conclusions

For the evaluation of cognitive and physical ergonomics, detached from interviewing a group of subjects, two methods were presented that can be used both in the development phase and for the later analysis of cabin ergonomics. The UASW method helps to systematically evaluate operating systems and classify their intuitiveness. A standardized evaluation scheme ensures that the subjective influence of the examiner is kept as low as possible. As in the determination of the technical value of design solutions, however, a small subjective proportion of the examiner remains in the result. Furthermore, the method does not claim to enforce ideal-intuitive operating systems, but is an aid in the selection and comparison of design variants that will never be without slight compromises after all. Figure 3 shows a model as the basis of the UASW method, which describes the subdivision of the usability of a product in functionality and operability. This subdivision is important in order to understand what an intuitive operating system needs - namely an operability designed as close as possible according to the population stereotypes.

The motion capturing method enables a purely objective recording of a subject‘s movements which can then be automatically analyzed and evaluated. So far, the system has only been used on non-moving tractors. The Kinect v2 camera provides good accuracy for the research described in this paper. The process reliability of the Kinect v2 was not always given in our experiments because measurements sometimes had to be repeated after the camera suddenly did not recognize a subject anymore during the measurement. With the acquisition of a new marker-based, professional motion capture system, process reliability has been achieved. The evaluation of the movements with comfort angles from the literature is expedient since the joint angles occurring during a movement or posture are crucial for the well-being and the health of the musculoskeletal system. Ergonomic literature provides many rating systems based on comfort angle specifications. In a first step, the traffic light system of the IFA (2015) was integrated into the evaluation algorithm. This can be replaced by other rating systems. The systems sometimes differ somewhat in their comfort angle specifications. The statistical analysis of the motion capturing method in our study shows that neither the age (22 to 62 years), body height (1.62 to 1.98 m), sex nor the type of use case (static/dynamic) have a significant impact on the valuation result. An expected but non-existent significance of the body height variable can be explained by the fact that each subject could freely adjust the driver‘s seat before the measurement and the adjustment paths were apparently sufficient. Therefore, the validity of the null hypothesis can still be assumed for all variables: The system can be used for body postures and movements and there are no special requirements for the subject group regarding the variance of age, body height, and gender. The feeling of the subjects is negatively correlated with the result of the evaluation system, for women this negative correlation is even significant. That does not seem plausible at first. Under the assumption of a successful verification of the measuring system used and calculation of the joint angles as well as a successful validation of the comfort angle specifications by the Institute for Occupational Safety, two reasons for the unsuccessful validation of the results of the evaluation system via the feeling of the subjects in this study remain. Possible first reason: The feeling of a subject group is not without exception the reality, because – as already described in the introduction – the perception of pain depends not only on biological, but also psychological and social circumstances. This would support the intention to establish a non-subject assessment process and allows the formulation of a hypothesis that needs to be investigated in further research: A group of subjects cannot evaluate gripping areas, postures, and movements to match actual biological impairment. Possible second reason: The assessment concept described in Figure 10 is not sufficiently accurate and needs to be adjusted. Adjusting screws could be a different weighting of individual joint angles or the system of classification. This would result in the development of a more precise assessment concept as a further research perspective. In general, it remains interesting to see whether in further investigations the null hypothesis from our study can be further confirmed or disproved – especially with regard to an expected influence of the variable "body height".

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