Chapter 13
Adaptive Workplace Design Based on Biomechanical Stress Curves

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Abstract The use of biomechanical models within the fields of workplace and working method design facilitates a detailed consideration of individual physiological capabilities and limitations. Based on motion capturing data of selected manual assembly tasks and the use of a biomechanical body model, body part-oriented stress curves for the upper extremities have been derived. This functional description of physiological stress allows a body part-oriented evaluation of movements and handling positions in the right grasp area. Furthermore these relations have been transferred into body part, movement direction and handled weight dependent linear regression functions. Thereby working system could be enabled to perform physiological stress-oriented self-optimization processes. Applied to manual assembly tasks and in accordance with the individual skills of employees these functions could be the basis for a physiological stress-related adaptive assistant system. Automation engineering, hence, can provide employee-specific support, e.g., in the supply of components or advices for adaption of working method. Working systems thus are able to optimize and adapt themselves to the individual needs and abilities of the employees.

13.1 Introduction

The competitiveness of production systems in high-wage countries can be maintained, among other things, by the development of the self-optimization capability of these systems (Brecher 2011, p. 2). The performance of these socio-technical

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systems has to be expanded by adaptive target systems and by reactive systems behaviour (Brecher 2014, p. 3). This requires each element of the production system, i.e. human, technology and organization, to have adaptive capabilities. According to Frank (2004), this means that each element repetitively performs these steps: 1. Analysis of the present situation, 2. Determination of systems objectives and 3. Adaptation of systems behaviour.

Humans are standing in the main focus of this approach. Consequently, the interaction of humans, production technology and organization elements is a topic under comprehensive study. However, these studies focus mainly on cognitive processes (Brecher 2014, p. 65; Mayer 2012; Mayer et al. 2013). Among other things, in the interaction of humans and technology the conformity of technology behaviour with the human operator's expectations is in the focus of these studies (Mayer 2012; Mayer et al. 2013). On top of this, holistic inclusion of humans for the purposes of ergonomic and industrial engineering research also requires direct consideration of the physiological processes involved. This is necessary in order to reach the optimum degree of integration of humans into a production system as demanded by Brecher (2011, p. 796) and, in this way, achieve the required increases in productivity. One possible approach to the inclusion of physiological processes in production systems in real time is presented and its results are discussed below.

13.2 Capabilities of Existing Methods of Workplace Design in Context of Self-optimizing Production Systems

Integrating physiological processes in the self-optimization cycle of a production system requires real time detailed assessment of the physiological status of persons. Several comprehensive approaches are available to analyse and evaluate work processes from a physiological point of view (cf. Hoehne-Hückstädt 2007). In terms of prospective workplace design these procedures allow working systems to be designed in line with the requirements and capabilities of persons (Schaub et al. 2013; Caffier et al. 1999). There are also some approaches explicitly taking into account the individual prerequisites of physiological performance (cf. Sinn-Behrendt et al. 2004). With respect to a discrete working process, procedures are employed either in advance or ex post facto. They are used preventively as well as for correction in the design of working systems. It is not possible to employ these procedures within the framework of production systems with real time capability.

For this purpose, only physiological measurement techniques have been appropriate so far, such as electrocardiograms, electromyograms, or combined methods, such as the CUELA system (Ellegast et al. 2009). The use of these measurement techniques allows data discrete in terms of time to be collected about the physiological strain situation of persons. However, their use needs extensive

technical measuring systems, which is possible only to a limited extent in industrial everyday practice and thus restricts the applicability of these procedures.

Consequently, new approaches must be developed which require as little equipment as possible and provide real time indicators of the individual strain status. At this point, above all digital human models are of particular interest. The progressive development specifically of biomechanical human models opens up new possibilities to ergonomic research. This could be a new basis of a more comprehensive inclusion of persons in the process of self-optimization of a production system.

13.3 Use of Biomechanical Human Models for Workplace Design

At the present time, anthropometric and biomechanical human models represent the standard tools of modern workplace design (Bubb and Fritzsche 2009). It is, above all, the biomechanical human models which allow new perspectives to be developed in workplace design. Whether and to what extent these models are able contribute to solutions of open problems in ergonomic research, such as the real time indication of physiological strain, have to be investigated.

In context of this research question, biomechanical human models allow advanced analysis of workplace design and of the interaction of humans and technology more than would be possible with anthropometric models. Models, such as alaska/Dynamicus or the AnyBody Modeling System (Damsgaard et al. 2006), permit in-depth study of the reaction of the musculoskeletal system of persons under the impact of mechanical loads. Workplace design can thus be examined at the level of effects of physiological stresses, and will thereby supply advanced strain indicators (cf. Fritzsche 2010). The use of these models makes it possible to describe, in formal terms, the effects of stresses acting within humans. Compared to the Dynamicus human model, the AnyBody Modeling System (Version 6.02) contains a detailed model of the human muscle system (Damsgaard et al. 2006). It can be used to derive information about the respective physiological strain situation corresponding to the muscle activation computed by the model. Furthermore based on muscle force output an advanced strain indicator is given (Cutlip et al. 2014; Rasmussen et al. 2012). This makes the model suitable for determining effects of physiological stress relative to specific parts of the body.

However, reference must be made at this point also to the respective validity of the model with regard to the muscle forces calculated (cf. Graichen and Deml 2014; Günzkofer et al. 2013; Nikooyan et al. 2010). To bear this fact in mind, the results explained below are interpreted not as relative values, but as values on an ordinal scale (Rasmussen et al. 2012), and only groups of muscles, no individual muscles, are considered.

Nevertheless, there is the possibility to contribute to closing the gap mentioned above in the inclusion of physiological processes within the frame-work of work-place design, and fill this gap in connection with self-optimizing production systems. It has been shown in a current research project that the use of the AnyBody biomechanical human model allows an evaluation of muscle load cycles for specific parts of the body to be performed within the framework of manual assembly processes. Moreover, it was possible to derive biomechanical characteristic curves to determine muscle activation in specific parts of the body. These characteristic curves can be the starting point in assessing a stress situation in real time within the framework of self-optimizing production systems. In combination with a suitable scene recognition, e.g. by means of a Kinect camera system, this makes it possible, in a working process, to determine in real time the change in muscle stresses with respect to specific parts of the body. The working system can thus respond adaptively by indicating individual limits of maximum permissible loads on specific parts of the body. Based on this knowledge the production system could deliver in real time precise advices and specifications to adapt the workplace design or working method.

13.4 Approach for Body Part-Oriented Indication of Physiological Strain in Real Time

In the study, the muscle forces relative to specific parts of the body were calculated on the basis of the AnyBody biomechanical human model. The model represents the human musculoskeletal system as a rigid multi-body model. Using inverse dynamics the model, taking into account interaction forces with the environment and a present kinematics of the individual rigid bodies, calculates the required muscle forces for the considered movements. These constitute the basis from which to derive the biomechanical characteristic stress curves. In line with the anatomical positions of the individual muscles, the muscle groups related to specific parts of the body are set up as follows: forearm (FA), upper arm (UA), shoulder (S), neck (N), and back (B).

The kinematics was logged by an infrared tracking system made by the VICON (MX 13) company with a scanning frequency of 200 Hz. The test setup employed a total of 13 infrared cameras for recording movements. The ground reaction forces were recorded by two AMTI (Advanced Mechanical Technology, Inc., Watertown, MA, USA; 1000 Hz) force plates. For further use in the AnyBody Modeling System (Version 6.02), these data were 2nd-order Butterworth filtered with a cutoff frequency of 12 Hz. Subsequent processing of the data was carried out with the Vicon Nexus 2 (Version 4.6) software.

The test persons were selected on the basis of DIN 33402-2. The selection of test persons followed the anthropometric data of German males 18–25 years old of the 50th percentile with respect to the body height as indicated in this standard. The 16
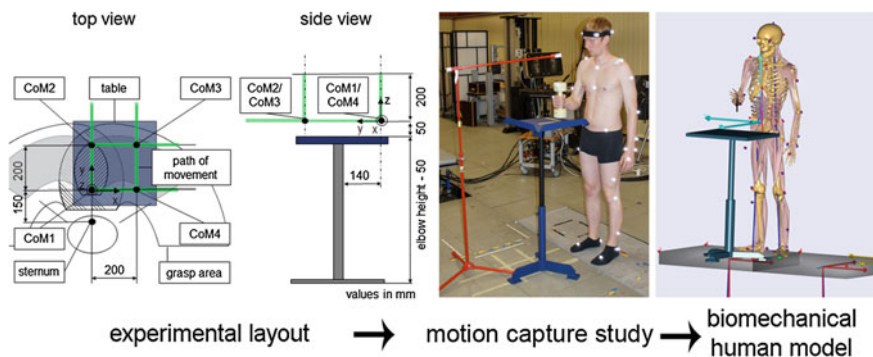
Fig. 13.1 Test setup and modeling in the biomechanical human model

male test persons of the study were all right-handed, had an average body size of 1.784 m (SD 0.013 m) and an average age of 26.6 years (SD 3.2 years).

The study dealt with simple manual assembly movements. In accordance with the MTM basic system (Bokranz and Landau 2011, p. 424) single-handed movement with handling of two different loads (M1 = 1 kg and M2 = 6 kg) have been analysed. The test design included linear movements (length of movement 20 cm) at four points (CoM—Coordinate of Movement) in the right grasp area in three directions positioned orthogonal relative to each other (DoM—Direction of Movement). The experimental layout, a picture from the motion capturing study and the biomechanical model of the AnyBody Modeling System with the applied ground reaction forces and force vector of the handled weight are shown in Fig. 13.1.

As a result of the study it was demonstrated that for the analysed movements activations of muscles relative to specific parts of the body as a function of the length of movement can be described in functional terms by linear regressions ($R^2 > 0.7$). Differentiated by parts of the body (FA, UA, S, N, B), coordinates of movement (CoM 1–4), directions of movement (DoM x, y, z) and weights (M1, M2) to be handled, this was converted into 120 linear regression functions for functional description of body part-oriented stress, in terms of muscle activation, for the execution of the linear movements considered in the right grasp area.

These characteristic curves can constitute an advanced basis of indicating, for specific parts of the body, physiological strain in real time. As a function of the respective position in which an activity is executed, activation of muscles in a specific part of the body can be determined, and the strain acting on these parts of the body can be indicated. Knowing the change in muscle activation as a function of movement and direction can be used to forecast its changes in real time. Either changes in the working method can be derived in order to adjust or reduce a current stress situation and individual strain level, or suitable support functions can be proposed, such as a change in the placement of material at the workplace. The characteristic stress curves constitute the basis of a comparative assessment of strain level encountered at a manual assembly workplace without the need for extensive measuring gear.

13.5 Use of Biomechanical Stress Curves in Context of Adaptive Workplace Design

For further analysis of the findings of the study, and to derive new approaches for workplace design, the data were examined in a variance analysis (ANOVA). The small sample size (n = 16), the data in part not following a normal distribution (Shapiro-Wilk test: $p < 0.05$) and, in some datasets, dissimilarity of variances (Levene test: $p < 0.05$) do violate the preconditions of an ANOVA, but it was carried out nevertheless. To meet the data situation under these conditions, an additional non-parametric test, the Friedman test, was performed with the Wilcoxon-ranking sum test as a post hoc test. The significance level was matched on the basis of the Bonferroni correction ($\alpha = 0.016$). Although its preconditions were violated, the findings of ANOVA were confirmed by the non-parametric test.

Table 13.1 lists the results of the analysis of variances. They indicate the partly significantly different body part related muscle activations. The table shows a comparison of pairs of muscle activation relative to body parts between two directions of movement (DoM: x—to the right, y—to the front, z—to the top) as a function of the coordinates of movement (CoM), body parts, and weights (M1, M2). The direction of movement with the comparatively higher muscle activation is indicated in all cases. The fields marked in colors characterize significant differences (power ≥ 0.7) in direction-dependent muscle activation per body part.

It is evident that, even with the simple movements studied, significant body part related differences in muscle activation can occur. The number clearly increases for weight No. 2. Among the movements studied, most of the significantly higher muscle activations were found in the shoulder and the neck. Moreover, movements

Table 13.1 Differences in body part related muscle activation per coordinate of movement (CoM), direction of movement (DoM), and weight (M)

M	Δ in DoM	CoM 1 body part					CoM 2 body part					CoM 3 body part					CoM 4 body part				
		FA	UA	S	N	B	FA	UA	S	N	B	FA	UA	S	N	B	FA	UA	S	N	B
	X-Y	y	y	x	y	x	x	y	x	x	x	x	y	x	x	x	y	x	x	y	y
M1	X-Z	z	x	x	z	x	z	x	x	z	z	z	z	z	x	x	z	x	x	x	x
	Y-Z	z	y	z	y	y	z	y	z	z	z	z	y	y	z	z	z	y	z	y	y
	X-Y	x	x	x	x	y	x	y	x	x	y	x	x	x	x	y	x	y	x	y	y
M2	X-Z	z	x	x	z	x	z	x	x	z	z	z	z	x	z	z	z	z	x	x	z
	Y-Z	z	z	z	z	y	z	y	z	z	y	z	z	z	z	z	z	y	z	z	y

FA – Fore Arm, *UA* – Upper Arm, *S* – Shoulder, *N* – Neck, *B* - Back

especially in the x- and z-directions result in significantly higher muscle activation than movements in the y-direction.

These findings can now become the basis of an adaptive workplace design. The differences in body part related muscle activation can be employed mainly in self-optimizing systems. On the basis of scene recognition, body part related strain indicators can thus be collected in real time on the basis of the body part-oriented biomechanical stress curves, and filed. If the work process is to include movements with repetitive high muscle activation of the same body parts, it could be assumed that strain level will increase in the body parts concerned, with the result that fatigue can occur in combination with possible discomfort in the execution of the movement and changes in movement as a result of fatigue. Consequently, the elements of the musculoskeletal system involved in the movement, such as ligaments, muscles and joints, may be damaged. Allowing the system to intervene at this point, e.g. by changing the working method in accordance with an underlying precedence diagram of the assembly task, or by adapting the workplace design with a resultant change in the method of working, can reduce fatigue phenomena resulting from singular body part related muscle activation.

Moreover, the results of the study can constitute the basis of more detailed planning of working methods. As the level of body part related muscle activation is known for the movements considered in the study, these basic types of movement as defined in accordance with MTM, such as "Grasp" and "Bring," can be assigned to specific body part related muscle activities. In defining a working method on the basis of the MTM approach, combinations of basic movements with high activation of identical body parts can be identified and avoided. Besides taking into account parameters of time, distance, and weight, planning of working methods for the first time can also consider the direction-dependent influence on the strain situation of individual body parts of the personnel.

In addition, the outcome of the study can be applied also in taking into account individual performance preconditions in workplace design. On the basis of individual capability profiles which include restrictions in the execution of specific movements or application of forces, the characteristic load curves allow the working system to be adapted specifically to workers. In this way, an adaptive workplace and method design guided by individual performance preconditions and with real time capability is created which can adapt itself to any situation within the framework of self-optimization of the production system as in a control loop.

13.6 Conclusion and Outlook

The data about body part related indications of strain elaborated in this study can only be a first step in the further integration of the biomechanical human model for workplace design. The biomechanical characteristics of body part related muscle forces initially apply only to the grasp area studied and the group of test persons considered. Consequently, the approach presented here must be extrapolated to

other areas of the grasp area and to a heterogeneous group of test persons if a complete description of biomechanical stress functions is to be achieved. This will be the basis of a more far reaching use of the characteristic body part-oriented stress curves within the framework of self-optimizing production systems for a variety of manual work processes.

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