Towards a Database for Deriving Design Aspects of Industrial Exoskeletons

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Abstract **– Industrial exoskeletons aim to physically support humans in individual support situations. One challenge exists in providing a comfortable fit and an appropriate support for specific users and tasks. As part of the DTEC-research project "EVO-MTI", typical working activities in production and logistics are exemplarily considered. Based on an anonymous description of demographic and anthropometric user data and multicriterial tool-based task analyses, several system requirement specifications are reasonable derivable for certain user groups and task profiles. The gathered aspects are numerically summarized in a database that is planned to be expanded by tasks, users, and body segments within the research project. Overall, this knowledge database represents the coupling element of the project-intended environment for developing and evaluating physical support systems like exoskeletons.**

Keyword – Exoskeleton, Industrial Application, User and Task Analysis, Database

I. INTRODUCTION

Technical support systems are increasingly used in occupational and daily activities to face the raising support demands of humans [1]. Selected general reasons might be the demographic change, increased product diversity and complexity, extended working lives, turnover of employees, and global competitiveness [2].

Industrial exoskeletons are a wearable support technology. They aim to support humans when performing physically demanding tasks [3]. For this, they usually transfer external system forces to the human musculoskeletal system by physical interfaces. However, industrial exoskeletons feature a different morphology (in terms of, e.g., path of force, materials, or actuators) [4, 5] and diverse technical properties (in terms of, e.g., supported body regions, height of support, or support control system) [6]. This causes a variety of possible system designs and a system customization for selected application scenarios [7, 8]. Their suitability is generally determined by aspects from the triad of human, system, and activity [9, 10].

For designing tailored physical support systems, the DTEC-research project "EVO-MTI" [11] aims to establish a design environment for developing and evaluating support systems on the application example of exoskeletons (see FIGURE 1). Its infrastructure distinguishes between three core elements and will mainly enable

1) the simulation and analysis of real application scenarios with mock-ups in a laboratory setting (with and without the use of different exoskeletons),

2) the simulation and analysis of exoskeletal properties with collaborative robots, as well as

3) the simulation of system users and the evaluation of exoskeletons with a humanoid or human-like testing machine.

Within the project period, different gathered data and derivable insights will be integrated into a coupling knowledge database for future decisions on system evaluations, optimizations, and designs. Accordingly, this emerging tool offers potential to revolutionise, ease, and improve the development process of physical support systems like exoskeletons.

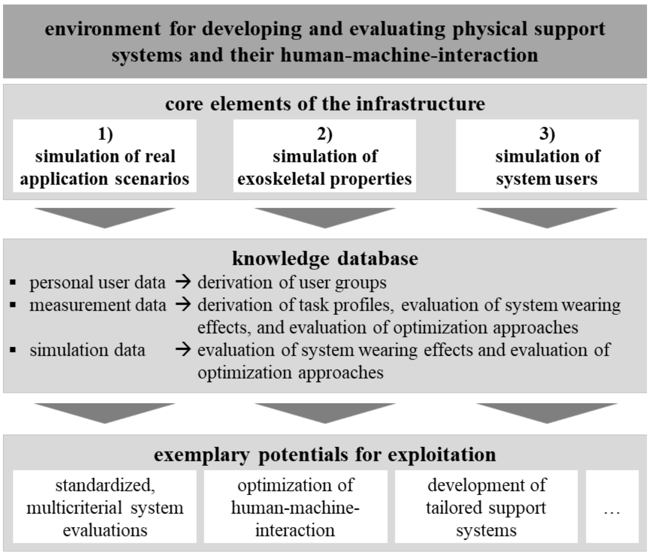

FIGURE 1: OVERVIEW OF THE INTENDED DESIGN ENVIRONMENT FOR DEVELOPING AND EVALUATING PHYSICAL SUPPORT SYSTEMS.

This paper mainly refers to the first aspect of "EVO-MTI" – the simulation of real application scenarios in a laboratory set-up, the structured storage of relevant acquired data into the knowledge database, and the derivation of required design characteristics of functional elements. It aims to reasonably define objective system requirements for the addressed use case, which is basically the first step of the transdisciplinary development approach of Weidner et al. [12]. FIGURE 2 summarizes the intended procedure for deriving these design aspects. It can be roughly divided into the phases of data acquisition, data analysis and processing, and exoskeleton development. In the following, the focus of the paper exemplarily lies on shoulder support systems. The use cases analysed and the database excerpts shown are also geared towards this exemplary application.

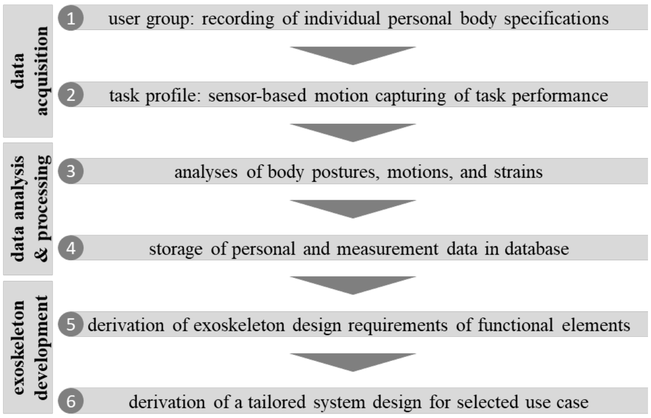

FIGURE 2: OVERVIEW OF THE PROCEDURE FOR DERIVING TAILORED SUPPORT SYSTEMS IN THE CONTEXT OF CORE-ELEMENT 1.

II. DATA ACQUISITION

This phase contains the data acquisition of the user group (step 1) and task performances (step 2) as fundamental basis of and relevant information for the database.

A. *Selected user group*

To demonstrate the general relations and functions of the database, an exemplary user group is consulted and consists of three test subjects (two males, one female). The selected test subjects feature a visible variance in body shape. Their demographic and anthropometric data are detailly summarized in TABLE I. The abbreviation "F" and "M" stands for "Female" and "Male", respectively. The dominant hand can be "Left" ("L") or "Right" ("R"). For anthropometric measurements, a measuring tape is used. The shoulder width is measured from the left to the right lateral edge of the acromion. The span is determined with laterally stretched arms from the left to the right wrist and elbow, respectively. The upper body length describes the distance from trochanter major at the hip to processus spinosus at C7. The upper arm perimeter is measured at biceps head. The pelvis perimeter is determined at the iliac crest.

TABLE I: DATASET OF TEST SUBJECTS.

criterion	***test subjects***		
	ID1	***ID2***	***ID3***
gender	F	M	M
age [years]	27	27	25
height [cm]	171.0	175.0	185.0
dominant hand	R	R	R
weight [kg]	72.7	85.0	72.0
shoulder width [cm]	35.7	41.0	41.5
wrist span [cm]	127.8	132.0	145.5
elbow span [cm]	83.3	83.0	92.5
upper body length [cm]	62.2	67.0	65.2
upper arm perimeter [cm]	25.5	32.0	27.0
pelvis perimeter [cm]	89.0	98.5	81.0
chest perimeter [cm]	89.0	104.0	93.0

A. *Selected task profiles*

In principle, there is a vastness of tasks in occupational and daily life, where exoskeletons are applicable. Within the exemplary investigation in this paper, the considered scenario is tailored on the production and logistics sector, and particularly on applications with mainly activities at head level or above. The task selection basically takes up task profiles of the developed test course of Ralfs et al. [13] that aggregated representative industrial tasks with similar characteristics to coherent clusters. This paper considers the tasks "overhead torquing", "grinding walls", and "clamping pipes". All tasks are displayed in FIGURE 3. The task selection considers diversity in motion, handled load, dynamics, handedness, and working height. All tasks are executed without wearing an exoskeleton.

Task A: Overhead torquing. In this task, the test subject holds an electric screwdriver (weight: approx. 2.55 kg) in the dominant hand and fastens a pre-fixed screw into a wooden beam at overhead level. The dominant arm is dynamically lifted and lowered from hip height to the wooden beam for each torquing. The height of the beam is individually adjusted so that each test subject has approximately around 90° shoulder and elbow flexion. Each test subject performs one repetition.

Task B: Grinding walls. In this task, the test subject holds a drywall grinder (weight: approx. 5.0 kg) in both hands and dynamically leads its head on a defined linear path and in a dominant direction of movement at the ceiling. The dominant hand is positioned in the middle and the non-dominant hand at the end of the handlebar. Each test subject performs four repetitions.

Task C: Clamping pipes. In this task, the test subject clamps a garden hose (weight: approx. 0.15 kg) with both hands in defined fixtures on a wooden board at overhead level. The task is comparatively static since both hands remain elevated above head level for a longer time. The height of the wooden board is individually adjusted so that it remains reachable for every test subject with almost stretched arms. The task is finished when ten clamps are fixed.

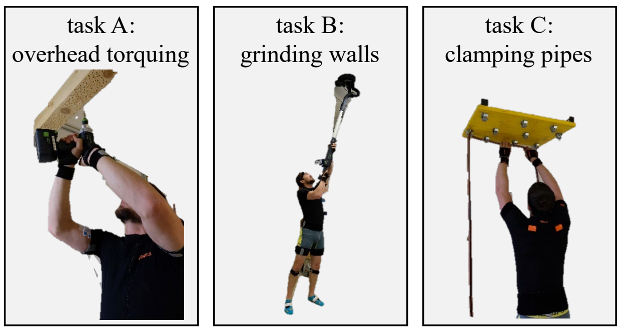

FIGURE 3: PERFORMED TASKS IN LABORATORY SETTING.

B. *Applied motion capture method*

The motion capture of each test subject is done with the system "MVN Awinda Analyze Pro" (Version: 2021.0.1) by Xsens [14]. It works with 17 inertial sensors that are fixed on defined body segments on head, torso, upper limbs, and lower limbs. Based on anthropometric input data of the respective test subject and an initial calibration, the system's software application compiles an individual digital human anatomical body model and calculates the kinematics of body segments.

III. DATA ANALYSIS AND PROCESSING

After successful user- and task-related data acquisition, this section describes the processing steps for analysing (step 3) and their storage in the knowledge database (step 4). Xsens is supplemented with the analytical software “INDUSTRIAL ATHLETE” (Version: 1.93.6) by scalefit [15]. This software builds upon the anatomical body model of Xsens and enables body strain analyses by considering the mass of body segments (based on measured body segment dimensions and a simulated body model) and hand-held loads.

C. Analyses of body postures, motions, and strains

FIGURE 4 displays the curves of shoulder flexion angles and shoulder joint torques for every task performed by test subject ID 3, since shoulder-supporting exoskeletons mainly address the support of this arm motion. A comprehensive overview of additional joint angles and torques could be added and would broaden the biomechanical representation of the specific tasks.

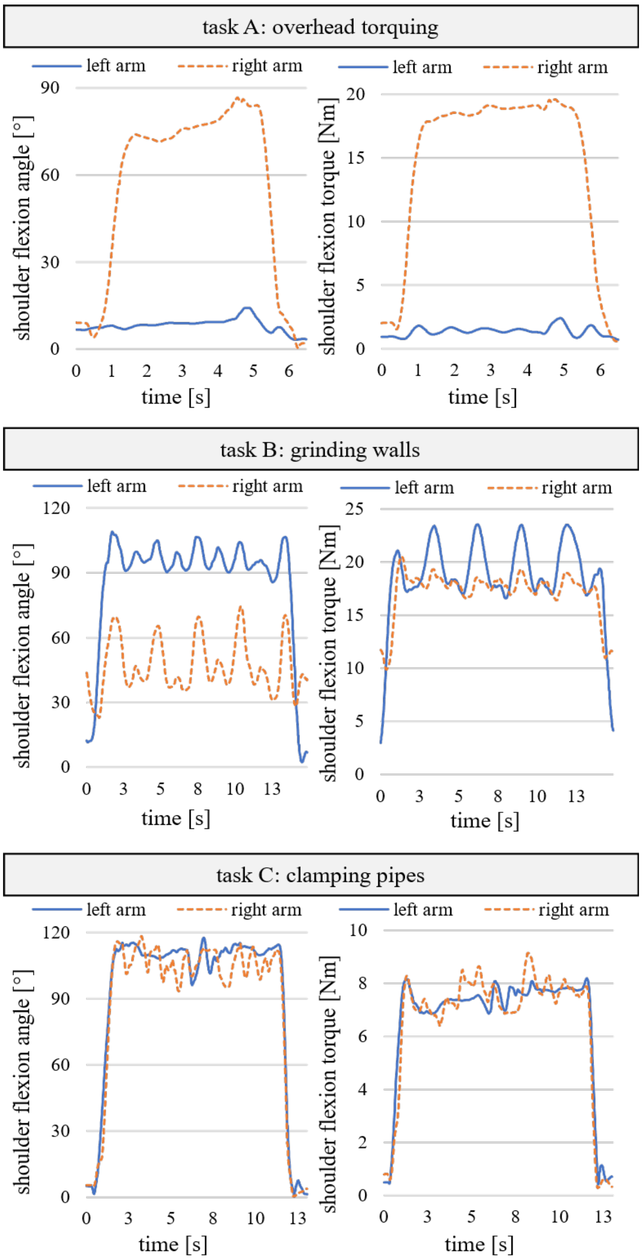

FIGURE 4: SHOULDER FLEXION ANGLES (LEFT) AND TORQUES (RIGHT) OF A SINGLE TEST SUBJECT (ID 3) PERFORMING TASK A - C.

FIGURE 5 displays the shoulder joint torques of all test subjects (ID 1-3) performing the same task (task A). As can be seen, variability in movement execution, speed, and body segment dimensions can lead to high variability in joint loads.

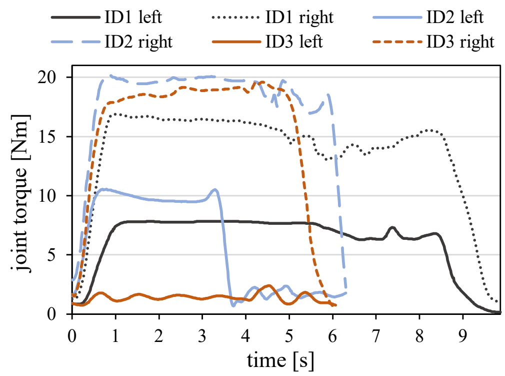

FIGURE 5: SHOULDER JOINT TORQUE FOR ALL TEST SUBJECTS (ID 1 - 3) PERFORMING TASK A (OVERHEAD TORQUING).

D. Storages into knowledge database

The relevant demographic and anthropometric data of the analysed user group and characteristics of task execution are stored in the knowledge database. To enable a simple data handling and further editing, the relational database mainly consists of numerical or binary parameters. Subscripted identification tags of analysed user groups and tasks are used to reach clarity, readability, and mapping. It is recommendable to work with individual codes like abbreviations, initials, and dates of investigations, so that a clear but data privacy compliant correlation is assured.

Table I contains the demographic and anthropometric dataset of every test subject. Based on this, Table II aggregates these data and summarizes the information of the analysed user group in total. The data are given with mean value ± standard deviation [minimum value; maximum value]. $U_{I:\,A,\,B,\,C}$ describes the values of user group I that performs the tasks A, B, and C.

TABLE II: DATASET OF USER GROUPS.

criterion	***user groups***
	$U_{I:\,A,\,B,\,C}$
number of males	2
number of females	1
dominant hand	3 x R, 0 x L
age [years]	26.3 ± 0.9 [25; 27]
height [cm]	177.0 ± 5.9 [171.0; 185.0]
weight [cm]	72.2 ± 9.8 [61.0; 85.0]
shoulder width [cm]	39.4 ± 2.6 [35.7; 41.5]
wrist span [cm]	153.1 ± 7.6 [127.8; 145.5]
elbow span [cm]	86.3 ± 4.4 [83.0; 92.5]
upper body length [cm]	64.8 ± 2.0 [62.2; 67.0]

criterion	user groups
	$U_{I: A, B, C}$
upper arm perimeter [cm]	28.2 ± 2.8 [25.5; 32.0]
pelvis perimeter [cm]	89.5 ±7.2 [81.0; 98.5]
chest perimeter [cm]	95.3 ± 6.3 [89.0; 104.0]

TABLE III summarizes relevant characteristics of the analysed task profiles performed by the user group $U_{I: A, B, C}$. It is done separately since task performances and body strains can differ between tasks (see FIGURE 4). Since values and curves can differ between test subjects (see FIGURE 5), the data is given with mean value ± intersubject variability. $T_{I: A, B, C: A}$ describes the values of user group I: A, B, C that performs the task A "overhead torquing". The shoulder kinematics are given for shoulder flexion and extension. Here, the maximum values can either arise when lowering or rising the arm. The extrapolated task repetition assumes an eight-hour-workshift without breaks. The further information values are coded as follows:

- The core activity has a dropdown menu of 1) "lifting / carrying", 2) "push / pull", 3) "screwing / drilling", or 4) "holding / stabilising".
- The working position can be differentiated in 1) "kneeling / squatting", 2) "upper body bending", 3) "upright standing", 4) "upright racking", 5) "sitting", or 6) "lying".
- The handedness can be 1) "singular", 2) "equally bi-manual", or 3) "unequally bi-manual".
- The room temperature can be 1) "< 10°C", 2) "10°C - 19°C", 3) "19-24°C", or 4) "> 24°C".
- The relative room humidity can be 1) "< 30%), 2) "30-60%", or 3) "> 60%".
- The regulation of personal protective equipment can be 1) "yes" and 2) "no".
- The available working space can be 1) "< 0.5 x 0.5 m²", 2) "0.5 x 0.5 m² - 1.2 x 1.2 m²), or 3) > 1.2 x 1.2 m²".

It should also be noted at this point that both some criteria in the database and their parameter values can vary for different use case scenarios.

TABLE III: DATASET OF TASK CHARACTERISTICS.

criterion	tasks		
	$T_{I: A, B, C: A}$	$T_{I: A, B C: B}$	$T_{I: A, B, C: C}$
shoulder flexion angle range [°]	L: 71.3 ± 50.4 R: 85.8 ± 7.4	L: 109.4 ± 16.0 R: 35.7 ± 11.3	L: 130.3 ± 22.1 R:121.6 ± 14.1
shoulder flexion torque peak [Nm]	L: 6.9 ± 4.1 R: 18.7 ± 1.5	L: 22.9 ± 2.8 R: 19.6 ± 1.2	L: 8.9 ± 1.8 R: 9.1 ± 2.1
max. shoulder joint acceleration [°/s²]	L: 713.4 ± 534.7 R: 511.7 ± 126.7	L:539.8 ± 240.1 R:420.4 ± 293.5	L:842.9 ± 117.2 R:809.8 ±104.9
max. shoulder joint velocity [°/s]	L: 129.6 ± 125.6 R: 118.1 ± 13.8	L: 140.2 ± 36.3 R: 64.7 ± 33.0	L: 155.2 ± 6.5 R:145.3 ± 19.7
single task duration [s]	7.5 ± 2.5	15.4 ± 2.3	14.6 ± 2.3
task frequency [1/min]	8.0	3.9	4.1

criterion	tasks		
	$T_{I: A, B, C: A}$	$T_{I: A, B C: B}$	$T_{I: A, B, C: C}$
extrapolated number of task repetitions	3,840	1,872	1,968
handheld load [kg]	2.55	5.00	0.15
core activity	3	4	2
working position	3	3	4
handedness	1	3	2
working distance [m]	0	0	0
room temperature	3	3	3
room humidity	2	2	2
personal protect-ive equipment	2	2	2
working space	3	3	3

IV. EXOSKELETON DEVELOPMENT

This section contains the derivation of exoskeletal design aspects of functional elements (step 5) based on the stored datasets of user groups and tasks. At this point, a concrete technical transfer guide for designing a tailored exoskeleton (step 6) is not intended since the exoskeletal design lately depends on individual design opinions, several technical and regulatory restrictions, and further circumstances. However, TABLE IV presents an abstract correlation of database criteria and functional design elements of a shoulder-supporting exoskeleton. It aims to address main exoskeletal design aspects like fit and adaptability, motion and movability, and support characteristics and shows which criteria can influence the respective design aspects of exoskeletons.

TABLE IV: SELECTION OF DERIVABLE EXOSKELETAL DESIGN ASPECTS.

exoskeletal design element	design aspect	related database criterion
structure	path of force (scope, size, adjustability)	• size and variabilty of body segments (i.e., shoulder width, upper arm length, upper body length) • maximum shoulder torque • handheld load • core activity • working position • handedness • personal protective equipment • working space
	material (rigidity, weight)	• maximum shoulder torque • handheld load • working distance
	degrees of freedom	• shoulder angle range • core activity • working position
	body proximity	• working position • personal protective equipment • working space
physical interfaces	position (lever arm)	• maximum shoulder torque • core activity • working position • personal protective equipment • working space
	shape	• sizing of body segments (i.e., upper arm perimeter, pelvis perimeter, chest perimeter) • maximum shoulder torque • handheld load • personal protective equipment

exoskeletal design element	*design aspect*	*related database criterion*
	material (breathability, padding)	• maximum shoulder torque • room temperature • room humidity
actuators	power	• maximum shoulder torque • handheld load
	capacity	• (extrapolated) task duration • task frequency • core activity
	dynamics	• maximum shoulder joint acceleration • maximum shoulder joint velocity • task duration • task frequency
	adaptability	• shoulder angle range • maximum shoulder torque • maximum shoulder joint acceleration • maximum shoulder joint velocity
	workspace	• shoulder angle range
	number	• handedness

In the following, some abstract examples for deriving objective design requirements of selected functional elements of a shoulder-supporting exoskeleton are given:

- Concerning the functional element "structure" and in particular the "path of force", the mean size and variability of single body segments of the user group hint the needed total size and adjustability of the kinematic back and shoulder structure.
- The intended level of support in reference to the occurring maximum shoulder torque helps determine its scope like direct flux from feet or hip to upper arm or hand-held tool. A redundant information about the intended level of support can be derived by the weight of the handheld load.
- The handedness and maximum shoulder torque of each arm can determine the necessity of having a support on both arms as well.
- Concerning another functional element like the actuator, its required power can be defined by the intended support level based on the handheld load or maximum shoulder joint. Its capacity can be determined by the daily operating time or the daily number of movements. For instance, passive actuators can be preferable for stabilizing tasks, whereas active actuators are more comfortable in dynamic tasks with frequent arm rising and lowering, which can potentially minimize the work effort against the system's support when lowering the arm. The latter might also be preferable for varying tasks and users with different working postures and support needs since support levels can easily be adjusted.

Finally, it is always recommendable to consider occurring joint angle and body strain progressions over time (see graphs in chapter 3.1) in addition to the numerical values in the database. This will enable a design of individual- or task-orientated appropriate support curves [16] in relation to, e.g., the shoulder joint angle and occurring body strains. Besides, the database can be supplemented by gathered data of the second aspect of the project, the simulation of exoskeletons with collaborative robots, as well as of the third aspect, the simulation of system users with a humanoid or human-like testing machine (see FIGURE 1). Both will provide valuable additional design information.

V. DISCUSSION

In this paper, the knowledge database with its procedure for data collection and derivation of objective design aspects for industrial exoskeletons based on simulations of real applications (see core element 1 in FIGURE 1) is presented on an exemplary level in terms of analysed user groups, tasks, and the addressed body segment. Even though it is neither representative nor comprehensive, the approach contributes to generally specify exoskeletal system requirements. At this point, it shows the potential of deriving selected, objective aspects and guidelines for designing shoulder-supporting exoskeletons due to a better comprehension of the addressed support situation with its representative characteristics. For this, the pursued inverse dynamics approach of "INDUSTRIAL ATHLETE" for calculating body strains is sufficient in terms of the calculation accuracy for the required database information as well as some aspects are in parts redundantly listed in the database in a different form of description or concreteness for designers. There is potential for exploiting the information collected in a structured manner in the database, for example with regard to carrying out a system evaluation, improving human-machine interaction, or developing tailored support systems. Though, any further dealing as well as the technical transformation and interpretation of respective database criteria still remain on an individual and creative level for designers. Similarly, the pure knowledge of system requirements cannot guarantee a reasonable technical realization of exoskeletal design elements. All in all, it is planned that the derived datasets and insights of core element 1 will be restored to the intended design environment (see core elements 2 and 3 in FIGURE 1) so that synergetic effects for developing tailored support systems to users and tasks will appear within the remaining project period.

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