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Human-Machine Integration as Support Relation: Individual and Task-Related Hybrid Systems in Industrial Production

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Abstract: One of the greatest societal challenges right now can be seen in the design of the interaction between human and technology. Especially in recent years this has become more intense. In almost all life situations, we are already supported or assisted by technology. Such systems come in various forms and characteristics. This paper will report on an ongoing research project named smartASSIST which aims to establish methods for the development of wearable systems for physical support as well as exemplary supporting technologies. The research is based upon a theoretical foundation of human-machine support relations which leads to the conceptual approach of constructing Human-Hybrid-Robot (HHR) systems.

Keywords: Support Technologies, interdisciplinary Approach, participatory Approach, Human Aspects, Human Machine Interaction, Wearable Technologies

1 Introduction

The design of interactions between humans and technology – especially with regard to demographic change as well as the more frequent and much more intense relationship in many areas of life – is one of the greatest societal challenges right now. First of all, such design has to take into account that these interactions are basically relations of support [19, 9, 6]. That is, humans and technology are both designed out of their joint operation in support situations. Technology is already supporting people in many areas of life. Health prevention is a particularly important domain in this respect. Regarding issues of musculoskeletal disorder (MSD) in an ageing work force, it is common to look at technology for some remedy. Relevant assistive and supporting technology will come in different forms and, in broader terms, as different technological artefacts, who reveal their potential in conjunction with its human users and the environment in which they are embedded. They can be substantially characterized in light of their abilities to support physical or cognitive human tasks. Depending on the task at hand, technical assistive devices and/or robots might take over the activities completely, thus acting often times in a different temporal-spatial field as their human counterparts.

However, (semi-) automated solutions are often only technically feasible or economically viable for simple and repetitive tasks. Consequently, there are numerous tasks in the world of work and in private environments that still have to be carried out manually because of their complexity or uniqueness [1]. In these areas, where assistive technology acts in close proximity and in collaboration with its user, e.g. in pushing-pulling or lifting tasks, technology and human beings can be seen as a single entity. This is one step further than simply looking for the design of their interaction. Therefore, the decisive challenge in development of these technologies, is not merely the development or the invention of new technology in itself, but a prognostic view of how future technology and humans might interact/integrate and what implications such newly “integrated entities” should have on strategic technology development. The relation between human and technology is not a zero-sum game. More technology does not necessarily mean less human abilities or even outright substitution of the human work force [14]. Unless this becomes clear, the potential of hybrid systems will always be prematurely criticized and thus consistently underestimated.

By designing the timing, coupling, and mutual control of the cognitive abilities and sensorimotor skills of humans on the one hand [22] in immediate connection with the reliability, speed, and force of technical artefacts on the other, we create hybrid embedded systems, de-

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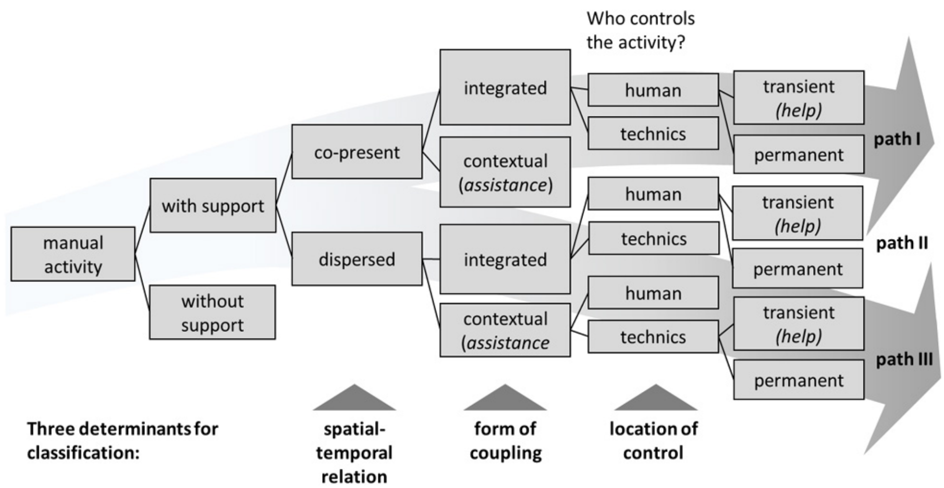


Figure 1: Paths for support activities (in extension to [19]).

ployed in responsible ways with potential to improve human health. New and promising approaches of technical support include body-related or wearable technical systems, e.g. classic exoskeletons for increasing power or systems for force redirection and support of cognitive structures.

This paper examines approaches and solutions for the support of ergonomic or quality critical manual tasks, e.g. in automotive, aircraft and construction industry. Based on main requirements and the approach of Human Hybrid Robot different context-adapted solutions are described. These include wearable systems for tasks at or above head level with handling of tools or components, for handling components as well as for gripping things. Moreover, the development of such user centered systems requires a participatory approach in order to increase the usability and probability of acceptance. Therefore, we will also describe some critical steps for facilitating this form of technology development.

2 The Basic Idea: Support Relations

The support of manual activities can be realized in different forms. The perception of the support depends significantly on the observer of the support-activity unit. [19, 8] An understanding of interaction patterns (interaction between a focal activity, e.g. task, and support) as well as the embedding of the respective coupling of activity and support is necessary for the design, optimization and selection of context sensitive technical systems [8]. For this purpose the definition of an "observer" as well as various determinants are helpful. The perceived support can vary depending on the selection of the observer (e.g. if the observer is the user/worker vs. if the observer is the producing company). Determinants serve developers and users to differentiate or classify support systems depending on the observation. Three basic determinants have been identified [19]. These include the spatial-temporal relation, the form of coupling and the location of control. An explanation of these determinants is given in, e.g., [19, 8, 9]. A classification along these lines proceeds by describing the form of support from general into more detail. A sketch of possible paths is illustrated in figure 1.

3 The Approach: Human Hybrid Robot

The concept of the Human Hybrid Robot (HHR) [17] presents one possible approach for individual support [20]. This concept can be classified somewhere between free programmable robots and manual workplaces. The basic idea is to support manual activities at work and in daily life by an intelligent coupling of human beings and technical components/systems (i.e. tools and mechanical functionalities or software functionalities like Poka-Yoke) into a hybrid and intelligent system [17], see figure 2. The crucial point can be seen in the integration of technical and biological elements as well as in the realization of a synchronous and bi-directional interaction between human beings and mechatronic and/or mechanic elements in a single hybrid system. Moreover, systems that are based on this approach, do not replace people by a technical automated solution, but support them instead.

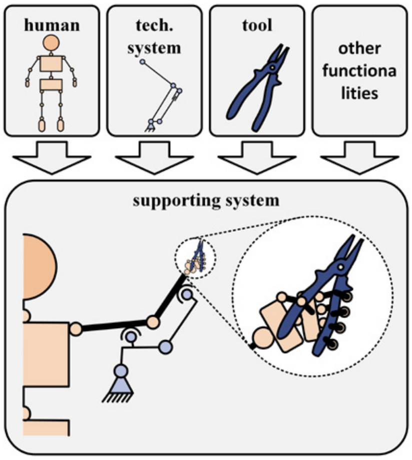


Figure 2: Concept of Human Hybrid Robot [17, 18, 20].

The HHR concept consists of a modular system architecture to allow for an ad-hoc configuration as well as a reconfiguration of systems. A construction kit with predefined hardware and software modules will be the result (see figure 3). This will be achieved by compliance to standards for e.g. interfaces. Modules have one or more functionalities and single functionalities can potentially be achieved by different modules, depending on their combination. Modules can be clustered into different classes by either their functionality or their technological classification, e.g. mechanical modules, biological modules, joints, algorithms, sensors, interfaces and so on.

All design and configuration choices regarding the technical support system are based upon human characteristics such as anthropometry, abilities or skill level in the specific tasks in which the system should aid its user. Additionally, the task itself, its complexity, overall load, frequency and duration have to be considered.

By combining the modules, support of human features and abilities can be realized, while human and technology form a single system. They are then working in conjunction, bringing together the strong assets of both parties, e.g. the keen sensory abilities of human beings and the high endurance of technical systems are used simultaneously.

4 Developing Wearable Systems

It is a common saying that the best system is the one people actually use. To come up with systems that will fit the individuals regarding their anthropometry, movement patterns, and functionality is clearly fundamental. But in order to approve of its usability, the technology has to prove its worth within the scope of their experience. Asking them beforehand about their needs and checking if the system meet the criteria after it has been developed is not sufficient, which is why we follow a tighter user integration in all development phases (see figure 4).

4.1 General Approach and User Integration

Developing wearable systems to the users' benefits is not a small feat. Though user integration is of course crucial for any other end-user-oriented product development processes, it is important to point out that this is even more the case for systems interacting so tightly with the user. Besides the close spatial coupling of user and system, creating plenty of pitfalls, another challenging aspect is the overall novelty of the subject. The experience of potential users with hybrid exoskeletal systems is mainly limited to what they have seen in movies and/or pictures. Therefore traditional means of generating requirements (e.g. questionnaire) are severely limited as potential users often lack the basis for describing what they want. Consequently, it is necessary to bridge the knowledge gap between users, which know the task/environment and the developers, which know, what is technically feasible and can assess what is medically appropriate in an iterative and explorative design process from both sides.

One way to do this is equipping the developers with sufficient knowledge about the characteristics of the conditions under which the work takes place and how the work is being executed. Therefore, as step one and prior to any technical developments, a thorough analysis of the workplace and the tasks at hand is commonplace. The analysis of working conditions contains the whole spectrum of influential factors on the working task from companies' organizational structures over the environmental surroundings (indoors, outdoors etc.), tools and artifacts being used, professional work ethics down to individual movement patterns of the single employee. For specific tasks, these individual patterns can be clustered into two or three distinctive ways of behavioral acts which in summary represent most work habits. Therefore, the workers perspective can be analyzed and integrated by way of external examination. We use ethnographic observation techniques to create pertinent thick descriptions of these aspects. These are not necessarily full blown ethnographies but sketches that are made whenever there is an occasion to do so: project meetings with partners, real world tests, or workplace visits.

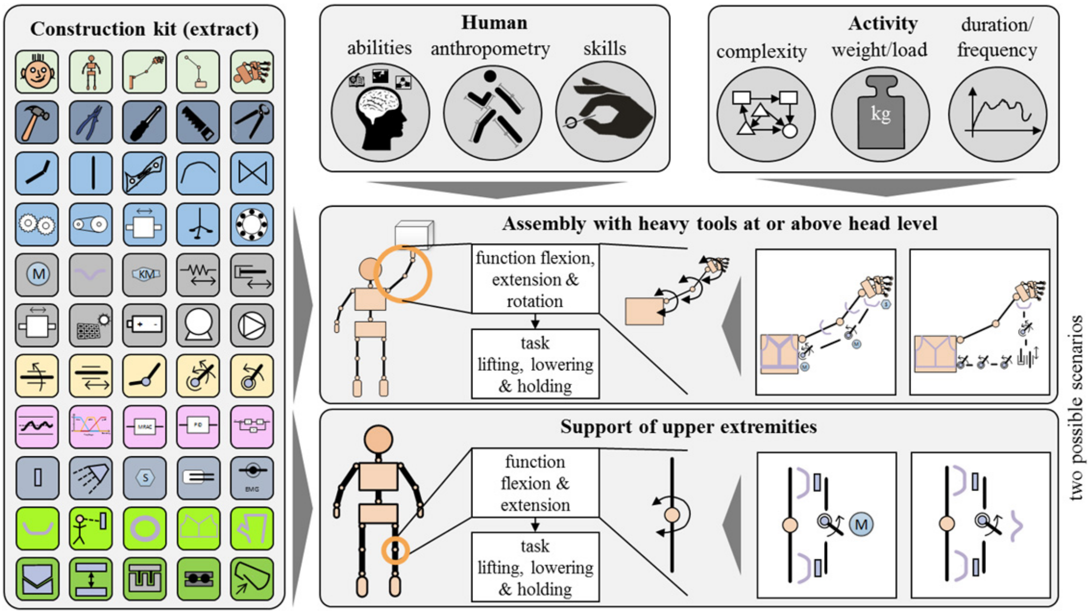


Figure 3: Construction kit systematic and exemplary configured system for two scenarios (based on [17, 20]).

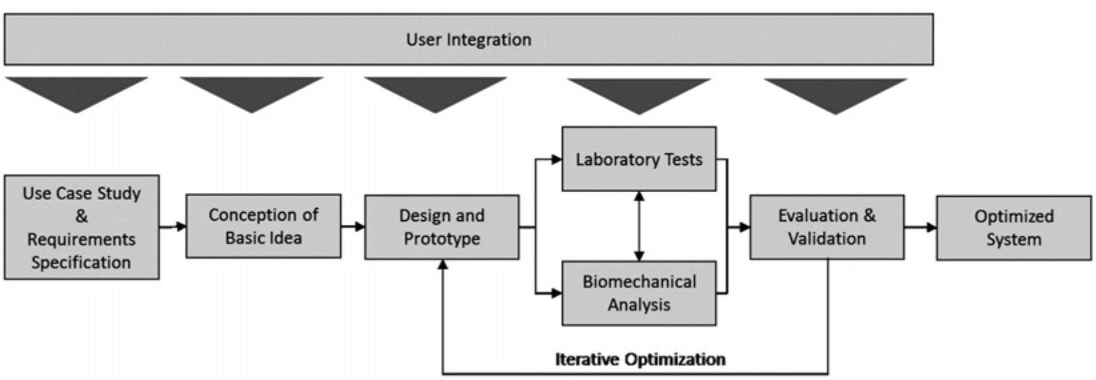


Figure 4: Transdisciplinary development approach.

Furthermore, the design of the technical support systems must be developed with the human body's capabilities and limitations in mind. In more detail, the general human physiological and cognitive abilities as well as their individual characteristics and individual skills are of great interest. When it comes to the specific working tasks, the complexity of the tasks, duration, frequency, and applied forces have to be known and accounted for in the conceptual ideas of the support system to be developed.

Since the initial workplace evaluation can hardly comprise every relevant aspect and during the engineering process different trade-off decisions need to be made, these decisions will need to be evaluated carefully using early stage prototypes. This has become easier in the last few years, as rapid prototyping technologies have become widely accessible and have established themselves as an indispensable development tool. By using these early stage prototypes it becomes possible to bridge the knowledge gap between users and developers much more easily. Additionally, they help to avoid pitfalls based upon wrong assumptions of the users' needs (e.g. users evaluated a stiff back structure positively, while developers considered it to be a problem).

Whether the developed system will actually help the user to accomplish her task or might act as additional burden is the key question when it comes to user acceptance. Based on the findings from step one, a concept can be developed on how the technical system should provide support. This includes the general system structure, how and when support should be given for the specific working task and which technical solution should be preferred over others. This concept will then lead to step three: the development of first prototypes. As soon as these prototypes are available, the users' input is necessary. Step three comprises an analysis of user interaction with the prototypes in two areas: 1) in the laboratory and 2) in the field. Inside the laboratory, user interaction is contained. It consists of the movement patterns and specific tasks which have been identified in step one. The focus of research is if and how the interaction with the system changes the original movement and how much of actual support can be measured via EMG and by user opinion.

These findings are compared to results during usage in the field. In field tests, more parameters such as the environment, additional tasks etc. affect the (perceived) support. Consequently, during testing in the field a biomechanical analysis is only an additional aspect of research among a broader scope of appropriate evaluation techniques from other disciplines, i.e. in our project above all sociology and production engineering.

Results of both areas influence further development and refinement of the system, as they are key aspects of the systems validation and assessment. This refinement and optimization cycle can take place more than once until the system reaches a sufficient level of support, user acceptance and technical readiness level. Embedded into this iterative optimization cycle is the systems fitting to the users' anthropometry. Apart from the different individual kinematics due to different movement patterns, anthropometry might differ significantly between employees. A wearable system, which will fit a variety of employees' bodies needs numerous settings to be able to change the size. Making every part of the system adjustable would increase the overall size and weight, which is one of the biggest problems of conventional exoskeletons [4]. To address this issue, a modular approach for the systems parts is helpful. In a modular approach, parts can be changed to fit different body sizes properly. On the other hand, this might lead to complexity and a large number of parts, which is leading to increased costs in turn. Therefore, during the development process, one has to find the right balance between adjustable and non-adjustable parts.

4.2 Examples

4.2.1 Work place analysis/identification of the most stressful task

In order to help reduce musculoskeletal load sufficiently, the tasks with the biggest impact on musculoskeletal disorder must be identified. One way of doing so, is to simply ask the employees what they think about which task is the most stressful for their bodies (e.g., by survey [16]). But in practice, this is not that easy. Most people do not distinguish their working tasks in such detail, as to be able to give a clear answer about the specific activity which will lead to the biggest musculoskeletal stress or disorder. Commonly, the effect of musculoskeletal stress aka "pain", will be a result of many different working tasks such as lifting, pushing or holding [10]. Especially if the stress on the body is caused by factors other than a single load like frequency and/or duration of the working tasks, it becomes difficult to tell which specific activity might be the most stressful. Additionally, general fatigue (mental and physical) can act as a contributor in the emergence of non-ergonomic behaviour at the work place [12].

One way to overcome this obstacle is to use pain as a proxy, that is, to take a look at the body areas where pain occurs e.g. by using a questionnaire. In conjunction with a deeper knowledge about the working conditions such as the ones mentioned before, an expert in ergonomics or biomechanics should be able to pinpoint specific activities out of the plethora of movements during the working shift, which are main contributors for musculoskeletal disorders. As soon as these activities are identified, the question arises whether they should be supported via a technical approach, e.g., a technical support system, or if other interventions like a change of the working conditions or educational instructions about ergonomics and working behavior are more likely to improve the situation. If a technical approach is inevitable or advisable, then it should focus on the key areas of necessary support.

When it comes to the validation of the concept by evaluating the prototypes inside the lab and the field, the main questions mentioned above have to be readdressed with the additional influential factor of the technical artifact and how it contributes to the assessed parameters' outcome.

4.2.2 Analysis of the baseline of physical activity

In lifting tasks for example, the lifting process can be mainly contributed by the muscles of the legs, the lower back or the arms. The share of each muscle group in performing a task depends on the lifting technique or the area of displacement of the object (e.g. from the ground onto a table or from one table to another). Therefore, a support device for lifting objects can support either the legs or the lower back or the arms or a combination of these, depending on the specific lifting situation.

Oftentimes, especially in complex body movements, the exact contribution of muscle areas is not exactly known. In these cases, the movements of interest are replicated in a laboratory environment to undergo thorough biomechanical analysis. Kinematic analysis with 3D motion tracking will help understand the motion and is the state-of-the-art technique to compare individual movements [3], e.g. of different employees (male, female, different anthopometry etc.). Electromyographical analysis (EMG) of the working muscles will provide an insight into the muscle activity, especially regarding the general activity level and with respect to the issue, which muscles are active at which point in time of the movement. The use of force plates or force sensors will give information about the overall load and/or applied forces during the task. Hence, this biomechanical analysis will provide a baseline of the activity itself, regarding movement, activity level and applied forces. All future enhancements, provided by the technical support system will later be compared against this baseline in one of the following steps of the development cycle. These measurements (3D motion tracking, EMG) also yield quantitive data which helps to integrate and evaluate user experience in general.

4.2.3 Research on force curves

In certain areas, this baseline will not be sufficient to know how much support is needed or in what manner the aided forces should be applied. This might be due to insufficient data on the human capabilities. E.g. human force is generated by the muscles not as a constant but as a force curve. That is, the amount of generated force is dependent on the corresponding segment angle [7]. Therefore, to provide the right amount of force, at least the conventional force curve must be known. As a result, further biomechanical analysis of these basic parameters of human capabilities are necessary if they are not available via literature [2]. Moreover, the right amount of support is key to develop systems which will help conquer the musculoskeletal overload without taking away too much effort of the user thereby maintaining physical capabilities.

5 Exemplary Solutions Different Applications

Based on the outlined theory for support, the approach of Human Hybrid Robot (HHR) as well as the basic approach for designing wearable support systems, we present exemplary solutions for supporting manual tasks in industrial production. These can help to compensate lost functionalities or improve the ergonomic conditions at the workplace. However, respective insights can also be transferred to other contexts, e.g., everyday life or nursing.

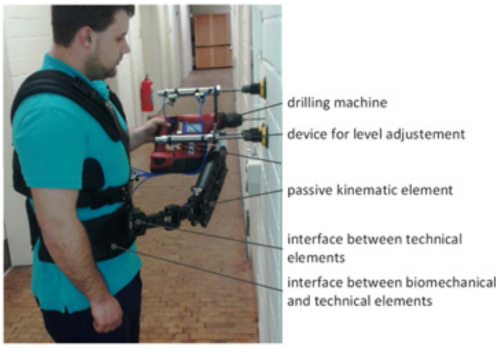
5.1 Support of Upper Body, Shoulders and Upper Arms

The physical support during manual activities such as the handling of tools or components at and above head level can be affected differently by wearable systems. A distinction can be made here, in particular, with regard to the diversion of occurring forces and the reinforcement of the user. Differences in the basic structure of the mechanical structure including the interface between the user and technical system mainly exist

- in the force path, along which the force – exerted by external loads – is transferred by the technical systems around body parts or regions,
- in the form of the coupling and arrangement of the technical elements interfacing between the user and technology, as well as
- in the internal structure and material of the elements forming the system.

Two examples for this use case are shown in figure 5 a) and b). The support system Jonny has been specially designed to handle tools. It is a wearable, passive, universal system with a tool attachment based on a Steady Cam mount (see [11]) and is equipped with a drilling end effector. Especially the upper extremities are relieved by this system. In addition, integrated components allow level compensation by actuators, a locking possibility is provided by suction cups and a distance sensor controls the drilling depth [18]. The wearable support system can improve ergonomics by transferring the weight of tools (and components) normally carried by both arms to the torso. In addition, the device can contribute to an increased quality due to the integrated level compensation as well as the locking possibility and depth measurement.

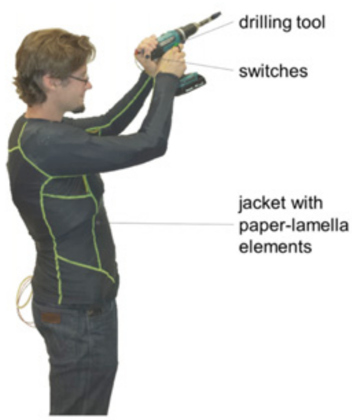
The support system Lucy is another approach for this scenario. The system supports the shoulder-upper arm area and does not initially provide a direct connection to the tool. The force is transferred to the pelvis using an exoskeletal structure for shoulder and back. [15] Pneumatic actuators or gas springs realize the support against gravity. The system Lucy reliefs the shoulder and upper arm during strenuous tasks at or above head level. In addition



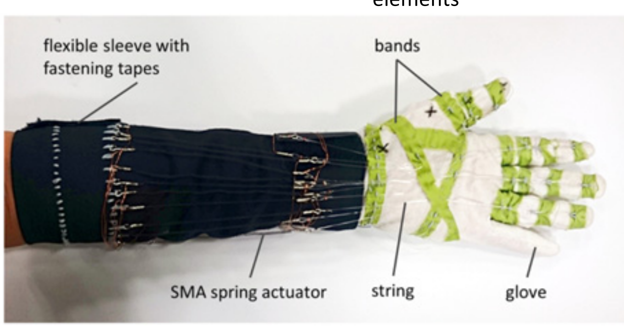
a) support system “Jonny” for handling tools

b) support system “Lucy” for tasks at or above head level

c) exoskeletal spine module



d) support systems with paper-lamella elements



e) muscle glove for support of gripping

Figure 5: Exemplary support systems for different contexts.

to physical support, we found evidence that work quality and accuracy are also improved. These effects will be evaluated in further experiments.

5.2 Support of Lower and Upper Body

Physically demanding tasks, especially in combination with a non-ergonomic posture, often lead to a high load on the lower and upper back [5]. As in the first application example, there are also different approaches. Two approaches are shown in figure 5 c) and d). Figure c) shows a multi-limb exoskeletal spine [13], which supports the back of the wearer with the aid of force, without limiting the freedom of movement. The exoskeletal spine structure is a technical backbone. Its rigid body elements are connected in series in such a way that the momentary poles of the technical system (each vertebral body) are coincident with the instantaneous poles of the human spine. This design allows a high degree of freedom of movement for the user and reduces relative movements (between user and system) at the interfaces/attachment points to the body. The support is provided by a connected actuator system.

The third variant, a variant with soft, textile-integrated structures, uses the paper lamella technique [21]. Various constructions are possible. On the one hand, the structure of the system is conceivable from a completely soft structure, with the three basic elements (elements with constant length, elements with variable length and articulation elements) arranged parallel to the human body depending on the necessary properties [21] (Figure 5 d)). On the other hand, a hybrid system element – soft and hard structural elements – is to be considered, for example, a hard interface to the shoulder with a passive, rotational degree of freedom and soft elements, which are coupled to the arm.

5.3 Support of Wrist and Hand

The hands are involved in almost all human activities. Individuals with a reduced manual function are therefore severely restricted in living their daily lives. Gloves with integrated actuators can be used to support hand activities. One approach is illustrated in figure 5 e). The muscle glove [23] replicates the biomechanical properties of the human hand. Technical tendons are actuated with a shape memory alloy. These act as an artificial muscle, in order to provide the forces required for the manual movement of the phalanxes. Using a multitude of individually controllable miniature shape memory actuators allows for a good replication of different hand positions and complex grip types.

6 Discussion

Support of human working conditions by wearable systems is an approach with a highly embedded technological artifact right in between the worker and the task at hand. Unlike other models of support, such as systems of cognitive assistance, the support (as well as any possible discomfort) is immediately felt by the user. Therefore an intuitive and individualized system is key. People might not know exactly what kind of technology they want, especially if the benefits are unknown. Thus, for the development of technology which operates in such close proximity to the user, we propose a tight integration of the user into the development process to gain as much information about the interaction between user, task and support system as possible. External expertise about human capabilities and adaptations to changes in work load induced by the system are an important asset. In order to keep the right balance between healthy effort and overload of the user, the system must not overcompensate.

Interaction between human and machine can take place in different levels of coupling. In opposition to more traditional approaches of human-machine interaction which consist of a temporally serial coupling (human and machine perform their tasks consecutively), the HHR approach melts this interaction between human and machine into a tight integration (hybridization). As the technology should adapt to the user and not vice versa, the technological solutions must be centered around the human needs and capabilities. Otherwise, the support system acts as an additional task to be maintained by the user, which could potentially lead to higher physical and cognitive interaction costs [22].

Regardless of the actual technical system or area of support the development process stays the same. Key aspect is a thorough analysis of the supported tasks and the movements it comprises. In order to come up with a technical solution to support the task, its characteristics must be understood. User acceptance is achieved, when the user itself is an integral part in various phases of the development. This will help to avoid dead end technologies, which are mostly an outcome of poor user acceptance. Furthermore, the tight integration of the user gives a deeper insight in the various parameters that have to be considered, such as kinematics, kinetics, movement patterns, anthropometry etc. The aforementioned method of development aims to pre-assess the key influential factors of working conditions on a multidimensional level and to integrate the findings into the system's basic concept. Nevertheless, the complexity of socio-technical arrangements makes it necessary to assess the feasibility of the technological approach by evaluating how the prototypes live up to expectations in real work environments.

7 Summary and Outlook

This paper has outlined the general approach of the HHR in the development of support systems for physical working tasks. The potential user, his needs and capabilities as well as the task itself have to be analyzed thoroughly, before the base technologies for the support system can be selected. Furthermore, the user should play an integral part in most research and development phases, as this enhances the acceptance of the final system by potential users in the field.

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