# Recupera-Reha: Exoskeleton Technology with Integrated Biosignal Analysis for Sensorimotor Rehabilitation

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**Abstract**

In this paper, the concept of the innovative exoskeleton for stroke rehabilitation of the Recupera-Reha project is presented. By applying innovative electromechanical solutions, advanced control approaches, and by using biosignal data, the system will be well-fitted. Furthermore, it will behave transparently to the user and will support different training modalities. The therapy situation will be supported and exercises in the field of everyday practice in the private or professional environment will be enabled. As an autonomous treatment system, it will give assistance as much as needed and will enable the patient to make therapies across sector borders (rehab-outpatient-work) for the first time.

**Keywords** full body exoskeleton, parallel kinematics, embedded distributed processing, assist as needed, EEG/EMG

**Kurzzusammenfassung**

„Recupera-Reha – Exoskelett-Technik mit integrierter Biodatenanalyse für die motorische Rehabilitation“ In Recupera-Reha wird ein innovatives Exoskelett für die Schlaganfallrehabilitation entwickelt. Durch elektromechanische Innovationen, fortschrittliche Kontrollansätze und die Nutzung von Biosignalen wird es von dem Patienten nicht nur gut tragbar sein, sondern sich auch erwartungskonform und den Intentionen entsprechend verhalten, um unterschiedliche Trainingsmodalitäten zu unterstützen. In der Therapie bietet es sowohl Übungsmöglichkeiten für die private Umgebung als auch in der professionellen Therapie. Als ein autonom agierendes System wird es nur so weit unterstützen, wie der Bedarf besteht und die Therapie über Grenzen therapeutischer Einsatzgebiete hinweg ermöglichen.

## 1 Introduction

Losing the capability to move (even a single extremity) is often associated with a reduction of quality of life of the affected person. Common causes of limited motor skills are often neurological diseases or injuries. In this respect, one of the most frequent causes of permanent disabilities in western civilization is stroke. In Germany alone, each year about $270,000$ people suffer from acute stroke [1]. Thus, in context of limited human and economic resources in an aging society, the need for effective and efficient rehabilitation measures increases [2]. In this paper, we introduce the Recupera-Reha project, which focuses on an innovative motor rehabilitation concept for stroke patients based on advanced exoskeleton technology with integrated biosignal analysis. The aim is the development of a safe, innovative, mobile, and self-sufficient full-body exoskeleton for upper-body rehabilitation. With the help of sensor fusion, the exoskeleton will provide an adaptive “assist-as-needed” control. Furthermore, to ensure the necessary autonomy of the user, all calculations (kinematics, dynamics, control, biosignal processing) will be performed in the embedded real-time control system of the exoskeleton. To detect the intended movements, to trigger feedback, and to allow for a support tailored to the user, the mechatronic system will be combined with an online evaluation of biological signals, i.e., signals that are generated by the human user (here the human’s electroencephalogram (EEG), electromyogram (EMG), and movement data). The application

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concept targets a direct compensation for movement restrictions. Hence, the facilitation of daily living tasks is possible and due to the highly adaptive control strategy, scientific knowledge of motor learning principles can be applied to the system. Furthermore, all innovations from the full-body system will be used to develop an independent subsystem in parallel. The motivation to develop the subsystems is to have a more focused exoskeleton that can be applied for tests in rehabilitation facilities in a short-term, while still enabling the focus of application of the system, i.e., upper-body rehabilitation. In the recent years different exoskeletons and orthoses were developed for rehabilitation purposes. Good overviews for example can be found in [3]. For a complex system such as an exoskeleton, differences in the approach will often apply only to parts, such as the mechanics, the control, sensors, or the usage of biosignals.

In this paper, we describe the development and the resulting challenges of an innovative sensorimotor recovery system that is easy to handle – an advanced and flexible rehabilitation tool for daily work with severely affected patients. These are essentially the therapy concept which must take up evidence-based therapeutic methods and the needed safe mechanical transparence in direct human robot contact. Furthermore, the electronic infrastructure needs to be modular, robust, small-sized, and computationally as well as power efficient. The workflow for dealing with a complex device as the developed exoskeleton requires complex software engineering. Moreover, online-algorithms that are required in kinematics and dynamics to control such a (highly coupled, high-DOF, multi-body) mechanical system have to be developed. The control architecture on joint level, apart from having a high level of accuracy, should offer a high degree of flexibility to cover the planned therapeutic approaches. The passive human (whose mass-inertia properties are unknown) and the active torque contribution of the patient must be integrated into the coupled control of the multi-DOF exoskeleton system. In the end the biosignal analysis has to cope with the changing characteristics of the patient's signals and the low amount of training data.

Besides the application scenario and therapy concepts (Section 2), main challenges and envisaged solutions will be discussed in the sections mechanical design (Section 3), electronic design (Section 4), kinematics and dynamics (Section 5), control strategies (Section 6), and biosignal integration (Section 7).

# 2 Therapy concept and application scenario

## 2.1 Target group

The developments within the project Recupera-Reha focus on the needs of stroke rehabilitation. Stroke plays a significant role for economic and socio-medical considerations (with regard to incidence and prevalence) [4]. The starting point of stroke treatments is the nature of the possible healing process of the disease itself: the brain is able to compensate lost motor function by neuroplasticity after a cerebrovascular accident. Therefore, neuroplasticity is the scientific basis for treatment of acquired brain injury with goal-directed therapeutic methods in the context of different rehabilitation approaches [5]. The long-term goal of rehabilitation is to improve movements for daily activities so that stroke patients can become as independent as possible. To achieve this goal, a number of evidence-based treatment methods have been established in recent years [6, 7]. Most of these methods are suitable for the transfer to the Recupera-Reha system. Moreover, the exoskeleton will offer the possibility to combine different treatment methods to develop innovative therapeutic concepts for stroke patients. For these reasons, stroke patients with moderate up to high limitations in motor function were selected as target group with further inclusion and exclusion criteria- for example: paralysis of upper limb at a 'Janda force level' 1-2 [8][1], at least wheelchair mobilization, and lack of a strong tremor.

## 2.2 Application focus and therapy methods

The application focus of the exoskeleton is as stated the rehabilitation of hemiparetic patients. About 35 percent of people who survived a stroke suffer from a chronic and often severe paresis [9], which complicate the self-sufficiency and the professional and social reintegration. Despite complex rehabilitation strategies, care, and compensation measures, the effects of the personal participation are not satisfying at all. The lack of effectiveness is caused by an insufficient systematic and effective approach of the intervention, a too low training-intensity, and too late therapeutic intervention [10]. This results in a reduced benefit for

[1] Janda force level: 1 = trace / recognizable reaction, not sufficient for a movement: about 10% muscle strength 2 = poor / movements in horizontal position possible, not against gravity: about 25% muscle strength [8].

daily activities. The innovation of Recupera-Reha is the possibility to support daily activities in a therapy environment, evidence-based therapies, and additional training capacity, which were shown to significantly improve the outcome of rehabilitation if extra training exceeds one hour each day [11], without additional personnel expenses. To achieve this, movement patterns of activities of daily living were analyzed for three healthy subjects based on a video documentation and 3D joint position measurements using the 'Neutral-Null Method' [12]. The spontaneously showing movements of the subjects were measured according to the standardized criteria of the joint angle profiles and the spectrum of a norm to be adopted is depicted. The natural individual variability of the joint movements was taken into account by an expansion of the maximum measured joint movements for the workspace of the exoskeleton by 20° in each direction. The defined workspace opens a wide range of highly individual movement options in the personal context.

High intensity of therapy, purposefulness, daily proximity, possibility of repetitive training of basic functions uni- and bilaterally, the activation of mirror neurons, and opportunities to self and circuit training are possible with the Recupera-Reha system and promise a comprehensive use and a maximum of effectiveness [13]. Furthermore, earlier studies showed that long-term training using biosignals induced partial neurological recovery in paraplegic [14] as well as in stroke patients [15], [16]. Soedakar et al. [16] could show that not only the amount of training but also the relevance of the trained behavior for daily activity has a strong influence on the improvement of motor capabilities of the patients.

### 2.3 Recupera-Reha therapy concept

The therapy concept follows an innovative dual approach strategy with the aim to combine activities of daily living (ADL) with evidence-based therapeutic elements (shown e.g. in [6]) to a holistic and innovative rehabilitation concept. The exoskeleton therapy is based on defined everyday activities such as lifting and moving a box or grasping a bottle on a table. Additionally, classical therapeutic elements in form of "therapeutic building blocks" supplement these tasks (e.g. bilateral repetitive practice or implementation of movement observation of the affected arm guided by the exoskeleton). In order to implement the therapy concept, the exoskeleton provides different operating modes: (1) assisted movements: this mode support the patient's movements via "assist-as-needed control";(2) teach in mode: a therapist guides a movement and the exoskeleton performs the recorded activity in a repetitive way; (3) master Slave: in this mode the movements of the healthy arm are mirrored for dual arm task in real time to the affected arm; (4) gravity compensation mode: the exoskeleton behaves transparently for the patient; (5) single movement: the exoskeleton supports isolated movements in individual joints via assist-as-needed. The "therapeutic building blocks" can be individually arranged to create a personalized robotic therapy to optimize the motor learning and healing process for the patient. All modes can be combined with a vibration or acoustic feedback if it is intended.

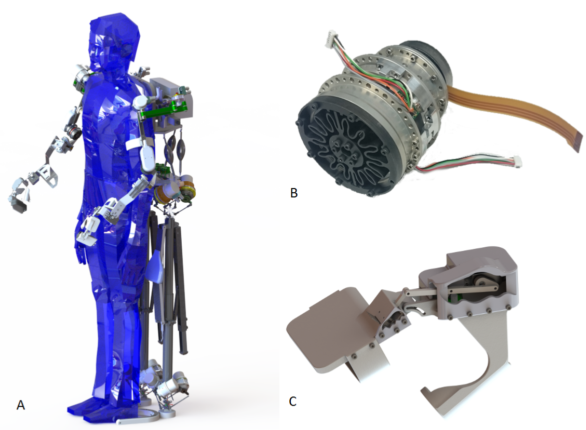


Figure 1: A: full-body exoskeleton. B: series elastic actuator used at the elbow. B: active hand interface support grasping tasks and hand opening.

# 3 Mechanical design

Due to its function as a human-machine interface, the mechanical design of the Recupera exoskeleton needs to ensure a safe and mechanical-transparent operation. In order to fulfill the implied complex requirements, the exoskeleton is composed of serial and parallel mechanisms. In Figure 1.A, an overview of the full-body exoskeleton is provided. For the actuation, it is planned to employ seven types of actuators: in dependence of the location of the actor within the mechanical system, the appropriate actuator type is dimensioned and designed. In the following, the mechanical design is presented in dedicated sections for the lower and for the upper body. In particular, the design provides the opportunity to split the exoskeleton in a lower and an upper part. It is intended to operate the upper part in combination with a wheelchair.

## 3.1 Lower body

A parallel mechanism, in comparison to a serial, offers higher stiffness, speed, accuracy, and payload capacity. On the other hand, it has a reduced workspace and a complex geometry that needs careful analysis and control. For the ankle and the hip joints, a novel parallel mechanism has been developed. This mechanism has three rotational freedoms and behaves like an almost spherical joint [17, 18]. Between the ankle and the hip joints a linear actuator will be integrated to avoid a heavy weight rotational knee joint. In the back of the exoskeleton, a hexapod is used to allow the patient movements of the upper body in relation to the pelvis in six degrees of freedom. The design process of all components follows a modular approach. In particular, actuators can be reused at different joints of the overall device.

## 3.2 Upper body

Since shoulders and arms require wide ranges of motion, serial arrangements of actuators have been chosen. The exoskeleton's shoulder mechanism consists of three rotative actuators whose axes intersect in the midpoint of the human shoulder. To avoid a collision with the human body, a six bar linkage with a virtual rotational axis is integrated into the shoulder mechanism.

For the lower arm, a serial kinematic is designed that covers the flexion and extension of the human elbow as well as the pronation and supination of the human forearm. In order to gain smooth movements, two types of serial elastic actuators are applied. The elbow actuator, depicted in Figure 1.B, delivers 2.7 Nm nominal and 12.7 Nm peak torque. It is equipped with a spring that is mounted between the gear and the actuator output shaft and that has been designed specifically for this application. The same principle is used for the forearm pronation actuator. Here, a Dynamixel servo with a nominal torque of 0.5 Nm is applied in combination with a special spring. An active hand interface supports the user to open the hand and to grasp objects (Figure 1.C). Here, a linkage with virtual rotation points allows the servo motor to transport the needed force to the end effector. At all contact points, six-dimensional force-torque sensors are applied to measure the human contributions to the motion of the exoskeleton.

# 4 Electronic design

The electronic design of the planned exoskeleton is shown in Figure 2. In total, the exoskeleton will be driven by 28 independent BLDC actuators, four servo motors and two assistance motors. Furthermore, power supplies and various different sensors (positions encoders, force-torque sensors, current measurement sensors, capacitive tactile sensors) are required to facilitate the operation of the system. Due to the complex electromechanical structure of the exoskeleton and the planned different support scenarios (where the partial, half, and full body exoskeleton subsystems are required to work independently), the architecture must follow for a modular design and support decentralized sensor data processing and motor control. Furthermore, the system has to operate autonomously and provide the possibility for embedded biosignal processing, which requires a powerful central control unit.

## 4.1 Decentralized first-level control

Each part of the exoskeleton contains a network of decentralized joint controllers containing a Spartan-6 FPGA [19, 20]. Each joint works as an independent processing unit and is responsible for the first-level signal acquisition and conditioning (e.g., Hall sensors, position encoders) and implements a cascaded control algorithm to allow a direct control and actuation of the attached BLDC- or servo motors. They are connected by a network with a tree-topology, the Node-Level Data Link Communication (NDLCom) [21]. This modular approach has several advantages over a centralistic design: (1) it provides a certain amount of intrinsic robustness, (2) allows to acquire and process signals directly at the site where the signals are acquired, (3) avoids peaks of processing and network load, (4) allows to divide the structure into independent sub-components, and (5) increases the safety and robustness of the exoskeleton.

### 4.2 Central electronics

The collection of the first-level data for the mid- and high-level control is delegated to the central control unit of the exoskeleton. The collection and processing of huge amounts of data from the distributed first-level controllers requires the support of massive parallelism for the initial processing steps. Furthermore, a mandatory requirement is the possibility to execute standard software. To fulfill these requirements, integrated System-on-a-Chip units such as the Xilinx Zynq are a possible solution, which combine a dual core ARM Cortex A9 processor and programmable logic (PL). Besides the processing that is performed on the CPU, the PL allows to use application specific hardware accelerators that provide massively-parallel processing power for time-critical and computationally expensive tasks. We will use an in-house designed electronics platform, the ZynqBrain [20](see Fig. 2, right side) that provides a tight connection to the first-level controllers. In the final exoskeleton, two ZynqBrains will be used: one will be responsible for the mid- and high level control of the exoskeleton itself, while the other will be responsible for the realtime processing of the biosignal data of the patient.

### 4.3 Power electronics

The power electronics of the exoskeleton robot is responsible for the power management of the robot. The main voltage of the system is chosen according to rehabilitation purposes with 48 V with a nominal current of 6 A for the upper body and 25 A for the lower body (the possible peak current is 30 A/50 A, respectively). In addition, 12 V and 5 V are used for the joint controllers and central electronics, respectively (with nominal currents of 3 A/1 A and 5 A/1 A for the upper and lower body, and peak currents of up to 10 A/2 A and 20 A/2 A). The power management is designed to supply the robot subsystems from three independent different power sources, which are the main power battery, the auxiliary system battery and the external power supply with in-system charging possibilities. The LiPoly batteries have a capacity of 5 Ah discharge currency. For safety reasons, the design of the battery packs will enable quick

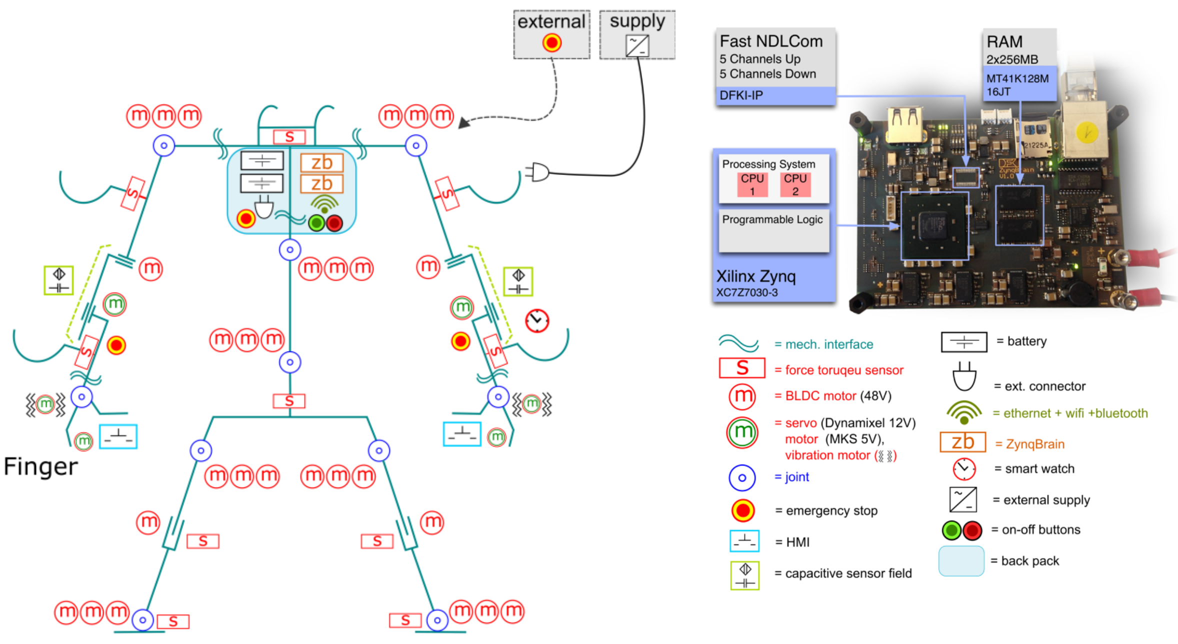


Figure 2: Left: Plan of electro-mechanical components within the exoskeleton robot. Right: The ZynqBrain processing platform used as central processing unit.

release of the battery to cut off the system from power. A battery design with fast release supports the usability of the system for extended therapy periods.

### 4.4 Embedded realtime processing of biosignal data

To enable a power efficient processing of the biosignal data in a small-sized system that it is embedded into the exoskeleton, the processing of the biosignal data will be performed by Dataflow-Hardware Accelerators (DFHWA) [22]. A DFHWA consists of a pipeline of heterogeneous nodes, each node provides the hardware implementation of a distinct signal processing and machine learning algorithm. The DFHWAs are located in the PL section of the ZynqBrain to enable a massively parallel processing of the high amounts of multimodal physiological data in real-time.

## 5 Kinematics and dynamics

### 5.1 Modeling

With regard to the Recupera-Reha project goals, three mechanical systems can principally be distinguished: (i) the mechatronic full-body exoskeleton, (ii) the biomechanical system of a human operator, and (iii) the coupled system of human and exoskeleton, connected by the mechanical interfaces (see Section 3). For each of these three systems, significant challenges exist due to their complexity: For (i), the employment of novel submechanisms, as, for instance, the Active Ankle (Section 3.1), as well as the overall (DOF) complexity need to be mentioned. For (ii), the modeling of the biomechanical system of the human body of an individual user is itself a highly complex task (due to the complex joints and the complex muscular actuation system). For (iii), the compound system of exoskeleton and human – whose motions are bind by the physical interfaces of the exoskeleton – is of particular complexity due to the various closed loops that are established by these contact points.

In spite of this complexity, a systematic workflow is required. At DFKI RIC, such a procedure is possible by using tools that allow the automation of the workflow in large fractions. In particular, using the software CAD-2-SIM [23], manual intervening becomes superfluous with respect to the complex numerical data that is needed to specify the kinematic and dynamic properties of three-dimensional machinery. Concretely, the CAD-2-SIM export of the mechanism design allows to generate specifications for libraries and frameworks such as ROS [24], ROCK [25], Openrave [26], and RBDL [27].

### 5.2 Algorithmic challenges

The operation of the exoskeleton requires the solution of several challenges of machine science. Broadly, these can be classified into (1) the problem of geometric-kinematic analysis (workspace analysis, singularity analysis), (2) the instantaneous-kinematic analysis (motion and constraint spaces), and (3) the dynamic analysis (low and mid level, see Section 6.1 and Section 6.2).

Due to the problems' interrelations, a precise, global offline analysis of the mechanisms workspace including its singularities is of crucial importance (1). The solutions of all other problems – in particular the online solution during operation – need to rely on such systematic analysis. From the algorithmic viewpoint, such an analysis represents the most demanding challenge. With regard to the problem classes (2) and (3), the question for necessary and sufficient precision are of importance in the domains of model descriptions and of conducted computations. In both aspects, a systematic workflow that incorporates a modular approach and (partially) automated tools is of crucial importance.

## 6 Control concept

According to the projected application, the exoskeleton requires a control concept, which covers the medical rehabilitation requirements and supports the innovative therapy concept.

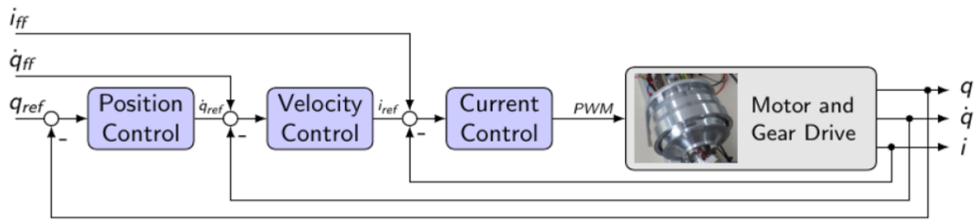


Figure 3: Low-level control architecture for actuators. $q$ is the angular position, $\dot{q}$ is the angular velocity and $i$ is the motor current.

### 6.1 Low-level control

The low-level control architecture for the joints of the exoskeleton is already implemented. It is cascaded and consists of a position, a velocity, and a current loop. Each actuator is driven by FPGA power electronics, in which the control software is implemented in a very flexible way. If desired, the control mode can be changed, which means each one of the control cascades can be directly selected for control. Figure 3 is a block diagram illustrating the joint level control architecture in the project. An advantage of this control architecture is the fact that the motors can be torque-controlled since it is well known that the torque generated by a motor is proportional to the amount of the current pulled by the motor. Furthermore, several safety mechanisms will be implemented at low level. To mention some, the position, velocity and current are limited via maximal values, and the control process is interrupted if the sensors fail at some point. This low level control architecture meets the requirements for the therapy concepts to be implemented in the final system and constitutes a solid foundation for both kinematic and dynamic control.

### 6.2 Mid-level control

A central idea in therapy concept is assist-as-needed control which requires efficient dynamics based control and estimation of active torque contribution from the human upper body. The exoskeleton arm is a 7-DOF multi-body system (including a passive DOF for flexion-extension movements of the hand and 1 active DOF for the hand interface) which wraps the complex human arm geometry with the help of three contact points which act as interface to the robotic system. Since the system will be equipped with the force/torque sensors at these contact points, the interaction wrenches $\boldsymbol{F}_i$ (composed of forces and torques vectors) can be measured at the three contact points in real time. The measured interaction wrenches can provide the net torque contribution to the exoskeleton system when multiplied by contact point Jacobian matrices $\boldsymbol{J}_i$. This torque contribution from the human is primarily composed of two parts: active torques ($\boldsymbol{\tau}_u$) provided by the human for the fulfillment of a certain task and passive torques ($\boldsymbol{\tau}_h$) which are needed to move the arm itself assuming no active contribution coming from the human (1).

$$\boldsymbol{\tau}_h + \boldsymbol{\tau}_u = \boldsymbol{J}_1^T \cdot \boldsymbol{F}_1 + \boldsymbol{J}_2^T \cdot \boldsymbol{F}_2 + \boldsymbol{J}_3^T \cdot \boldsymbol{F}_3 \tag{1}$$

In case of a healthy subject, the user can actively carry its own arm for performing any task and hence, $\boldsymbol{\tau}_h = \boldsymbol{\tau}_u$. In case of stroke patients, the patient cannot provide enough torque to move his or her own arm and hence he or she needs assistance from an active exoskeleton system. The time series contribution of the user can be summed up over one reaching movement using (2) [28].

$$\boldsymbol{C}_u = \frac{\sum_{t=0}^{T} \boldsymbol{\tau}_u(t)}{\sum_{t=0}^{T} \boldsymbol{\tau}_h(t)} \cdot 100 \tag{2}$$

The exoskeleton system can be modeled as a multibody system and its inverse dynamic model can be calculated with Lagrangian approach (3).

$$\boldsymbol{M}_r(\boldsymbol{q}) \cdot \ddot{\boldsymbol{q}} + \boldsymbol{C}_r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \cdot \ddot{\boldsymbol{q}} + \boldsymbol{G}_r(\boldsymbol{q}) = \boldsymbol{\tau}_r \tag{3}$$

Here, $\boldsymbol{M}_r$ is (5 x 5) positive definitive inertia matrix, $\boldsymbol{C}_r$ is (5 x 5) matrix containing Coriolis and centrifugal forces, $\boldsymbol{G}_r$ is (5 x 1) size vector of gravity forces, $\boldsymbol{\tau}_r$ is (5 x 1) size vector of the robot torques needed to perform the task. Similarly, the human arm can be modeled as another passive rigid multibody system as shown below:

$$\boldsymbol{M}_h(\boldsymbol{q}) \cdot \ddot{\boldsymbol{q}} + \boldsymbol{C}_h(\boldsymbol{q}, \dot{\boldsymbol{q}}) \cdot \ddot{\boldsymbol{q}} + \boldsymbol{G}_h(\boldsymbol{q}) + \boldsymbol{K} \cdot \boldsymbol{q} = \boldsymbol{\tau}_h \tag{4}$$

The mass-inertia properties of the different bodies constituting the human arm can be calculated by taking certain anthropomorphic measurements of the human. It must be noted that it is not easy to capture all the dynamics of the passive human arm because stiffness, damping and muscle tone are not well understood. However, assuming a linear relationship between arm configuration in joint space ($\boldsymbol{q}$) and unmodeled torques might be useful to estimate a part of it. This can be estimated for each patient during the calibration phase when the patient is passive.

The lower body control will be defined in such a way that it can support the weight of upper body system in sit and stand postures while performing rehabilitation therapy. For the future, it is planned to equip the exoskeleton with walking capabilities based on optimal gait generation (for example, see [29]).

# 7 Biosignal integration

By coupling the intention, e.g., inferred from the electroencephalogram (EEG), and the body's movement, monitored and supported by the exoskeleton and electromyographic (EMG) data analysis, we are able to reconnect the disrupted or disturbed loop between the patients's brain and body. In the following, the biosignal analyses are explained, which will be used to support the specific movements defined in the therapy concept and *known* by the exoskeleton (see 2.3). By executing intentions and by receiving a realistic feedback from the body, the rehabilitation process is strongly supported [15, 16].

## 7.1 Torque estimation based on EMG and exoskeleton movement data

Within the Recupera-Reha project muscle activity will be used to implement an assist-as-needed control. In practice, this control only supports the patient's movements to a degree that the affected extremity is always pushed to the edge of the current movement capabilities. The EMG signals from several muscles of the arm together with sensor information of the exoskeleton such as positions and velocities are fused and used to generate a model which predicts the generated torque within the joints of the human arm. These torques are forwarded to the control of the exoskeleton and directly affect the generated torques within the joints of the robotic system. In this way, an appropriate level of assistance is provided to the patient and an optimal training can be achieved.

To this end, experiments with healthy subjects were conducted. Within these experiments, subjects had to perform four different movements with varying weights in their hand. The movements were biceps curls, lifting the straight arm to the front and to the side and a grasping movement. The weights ranged from 0 kg to 2 kg in steps of 0.5 kg. Further, the joint angles were measured with the help of a Qualisys motion tracking system. The first analysis was done for the elbow joint. Therefore the torque in the joint was calculated based on the carried weight and the arm configuration. Additionally, EMG from the right arm (brachioradialis, extensor carpi, biceps big head, triceps long and lateral head and delta front, middle and back) was recorded. The EMG was preprocessed with a variance and a consecutive RMS filter. Afterwards, the muscle activation was estimated with a second order differential system, $p(t) = \gamma * e(t-d) - \beta_1 * p(t-1) - \beta_2 * p(t-2)$, with an electromechanical delay of $d = 50\,\text{ms}$, $\beta_1 = 0$, and $\beta_2 = -0.25$. The torque, angles and the muscle activation were used to train a K-Nearest-Neighbour-Regressor with $k = 1$. Based on the activation level and the angle the Regressor had to determine the torque. The first results can be seen in Figure 4.

## 7.2 Detection of movement planning based on EEG

The final exoskeleton will have the possibility to acquire and process EEG data online with the aim to detect the planning of movements [30]. This detection is achieved by using signal processing methods to enhance the low signal-to-noise ratio of the raw EEG data and by machine learning methods to distinguish

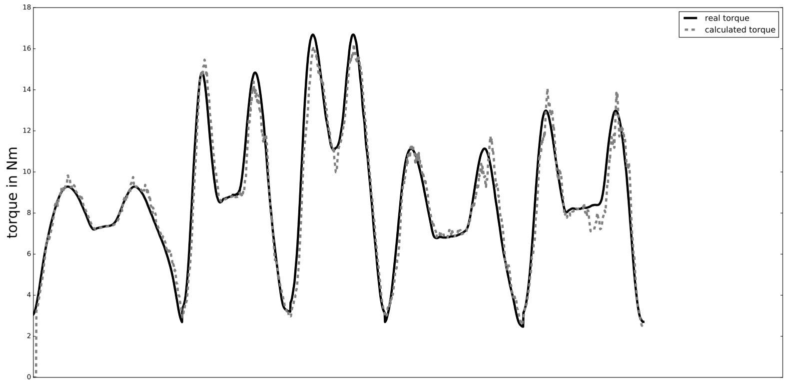


Figure 4: First results on torque estimation for the elbow joint.

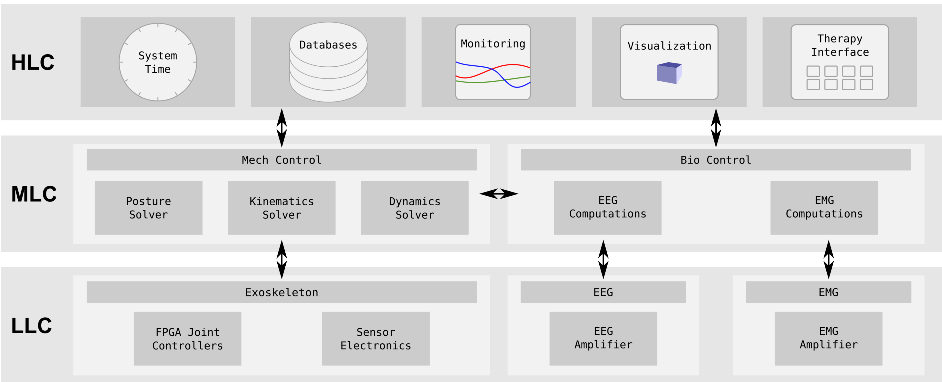


Figure 5: Overview of software components.

between movement intention of the affected arm and no movement intention. A special requirement for the processing is that models from other subjects and sessions have to be reused due to the lack of data from patients. Here, an online ensemble learning approach will be used to pretrain processing pipelines from the same patient and more importantly from healthy subjects to have a baseline where the brain function is not affected. Furthermore, to overcome the lack of training data, we will use regularized spatial filters that can deal with a low amount of data [31, 32] and generate artificial data from the original data. For the processing, we also pay attention to keep the computational load low to enable real-time processing on a mobile processing device inside the exoskeleton. The results of EEG analysis will be used in different ways. First, the assist-as-needed functionality can be further strengthened, e.g., by triggering the assistance when a movement intention is detected or by increasing the speed of the exoskeleton to reward continuous engagement. Furthermore, positive feedback via vibration or sound can notify the patient when the intention to move is present. Second, insights into the underlying brain activity will be provided to the therapist. To achieve this, we use source localization to get an estimate on which regions are involved in the tasks and the backtransformation [33] to find out which parts of the data are used by the classifier for the prediction of movements. Since the therapy of stroke patients is targeting the reorganization capability of the brain, this information can provide a beneficial add-on for the patient as well as for the therapist.

# 8 Summary and outlook

The prospective system of the Recupera full body exoskeleton has been presented together with a discussion of its capabilities and challenges. Subsuming, Figure 5 provides an overview about projected software components (and their interfaces) of the system, that arranges the software components within three layers: (i) The High Level Control (HLC) on the first layer offers functionality for ‘time synchronization’, ‘data storage’, ‘state monitoring’, and ‘therapy adjustment’ (Section 2). (ii) The Mid Level Control (MLC) layer is separated into a mechanical control, (Section 5, Section 6), and a biosignal control which influence each other (Section 7). (iii) The layer of the Low Level Control (LLC) includes the hardware-near components dealing with joints and sensors of the exoskeleton (Section 4, Section 6), as well as EEG and EMG data acquisition and digitalization (Section 7).

The exoskeletons, i.e., the part and the full-body system, are designed to work in the challenging task field of inpatient and outpatient rehabilitation to support classical therapy approaches as well as activities of daily living. To fulfill the manifold tasks and to be easy to operate, a very close cooperation between designer, programmer, and therapist as well as patients is required. Especially, it is essential that both, therapists as well as patients, are involved in the process of development and testing. To achieve this, a very close contact with inpatient and outpatient rehabilitation personnel and care givers as well as patients is established. Not only the final system but also in-between stages will be tested in rehabilitation facilities with the personnel as well as the patients at hand. In long term extensive tests, it is planned to study the expected positive effect of an intention-driven therapy system that allows to support self-initiated movements of different complexity.

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