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Design of the Pediatric Arm Rehabilitation Robot ChARMin

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Abstract— **In adult patients with motor impairments, such as stroke, actuated robots are available to provide an intensive rehabilitation training and to actively assist, enhance and assess neurorehabilitation. However, there is currently no actuated robot available specifically designed for the rehabilitation of children with upper extremity motor impairments. Therefore, ChARMin was designed, an arm exoskeleton robot to assist arm movements for young patients, especially children with cerebral palsy. The first prototype has four degrees of freedom for the shoulder and elbow. The design is based on a serial mechanical structure together with parallel kinematics for remote center of rotation actuation. This approach allows to keep a safe distance between parts of the robot and the patient and it reduces friction, while being highly adaptable to cover the large anthropometric range of the patients aged 5 to 18 years.**

I. INTRODUCTION

Children with a congenital or acquired brain injury often have impairments of their arms which affects their independence and participation in daily life [1]. Among these patients, one of the most prevalent neurological disorders affecting up to 2.5 per 1'000 children born in Northwest Europe [2] is cerebral palsy (CP). CP describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain [3].

The principles underlying motor recovery in children with CP are not yet completely understood, but first results suggest that motor rehabilitation in children has traits of motor learning in healthy subjects [4]. Moreover, there are indications that plasticity is enhanced in the child's brain so that recovery from brain injuries is more effective than in adults [5]. As in adults, an intensive therapy [6] and active participation [7] seems to be important for recovery and to prevent from declining arm functions in children with moderate to severe impairments [8].

In adult rehabilitation, actuated robots are more and more used, as they can provide intensive, repetitive and frequent training while assisting and assessing the patient. Moreover, robots have been shown to have a positive effect on the rehabilitation process in adult stroke patients [9].

In contrast to robot-assisted rehabilitation in adults, there are only a few robots that can provide active assistance for the pediatric arm [10]. First tests with actuated robots in children with devices originally designed for adults such as the InMotion2 [11] or the NJIT-RAVR system [12] have been conducted. These preliminary investigations indicate that children may benefit from actuated robots used during the therapy.

Here, we introduce a new actuated exoskeleton robot, ChARMin, that can be used for rehabilitation of children with impaired arm motor functions, such as CP. The specific research challenge in designing this robot was to find the optimal robotic system that satisfies the needs given by the clinical goals and settings, the safety constraints and the typical patient requirements and properties of the pediatric target group. A first prototype with four degrees of freedom (DoF) was recently finished, based on a previously presented concept [13]. In this paper the design of the ChARMin robot is presented together with a first evaluation of the technical feasibility.

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II. REQUIREMENTS

The concept and design for the ChARMin robot was influenced by various aspects and requirements:

a) Target group: The robot has to cover the age range from 5 to 18-year-old children with CP.

b) Anthropometry: In order to cover the different arm sizes of the target group, the robot must be highly adaptable. This includes the length characteristics for the upper arm (0.19 m ... 0.32 m), forearm (0.16 m ... 0.25 m) and the wrist-to-handle distance (0.05 m ... 0.08 m), the circumference for the upper arm (0.17 m ... 0.28 m) and forearm (0.17 m ... 0.26 m), as well as the sitting shoulder height (approx. 0.6 m ... 1.0 m). Anthropometric data were extracted from [14].

c) Kinetics: The robot needs to be strong enough to guide a paralyzed arm as well as to counteract a spastic arm. Furthermore, the robot should resist a strong patient when using the robot as an assessment tool to measure isometric joint torques. Therefore, data from healthy subjects were used to estimate the torques that the robot should be able to apply [13].

d) Range of Motion (RoM): The desired RoM that the robot should cover was based on recorded activities of daily living [15] and on additional feedback from the therapists in the children's rehabilitation center Affoltern am Albis, Switzerland. The four joints of the first prototype and the corresponding desired ranges are the shoulder horizontal add-/abduction ($-20°$ ... $+90°$), shoulder extension/flexion ($-58°$ ... $+152°$), shoulder internal/external rotation ($-47°$ ... $+54°$) and elbow extension/flexion ($+12°$ ... $+117°$).

e) Operability: The robot has to be easily adjustable to the patient's arm which also includes a change-of-side mechanism that allows the therapist to change between left and right arm training. Furthermore, the robot has to be mobile for transportation and positioning relatively to the patient.

f) Safety: In the adult ARMin robot [16], built at the SMS Lab, ETH Zurich, Switzerland, the horizontal shoulder rotation is actuated from top of the shoulder joint, leading to mechanical parts that are close to the patients head (Fig. 1, left). In contrast, ChARMin should use a kinematic designed that allows robotic parts to be further away from the patient's head and trunk. Moreover, the robot axes should have low backlash and backdrivable joints (static friction <1 Nm) that are movable in case of power loss. A mechanical gravity compensation system has to be included that keeps the robot passively balanced. Furthermore, mechanical end stops for all the axes and the possibility for quick release of the patient has to be provided.

g) Motivation: Motivation is crucial for children in order to promote an active participation and to increase the amount of repetitions during the therapy. An increased motivation can be achieved by game-based VR scenarios that account for the specific interests of children [17]. This VR interface combined with an appealing design of the robot and its use in non-distracting surroundings provides an environment for active and intensive training.

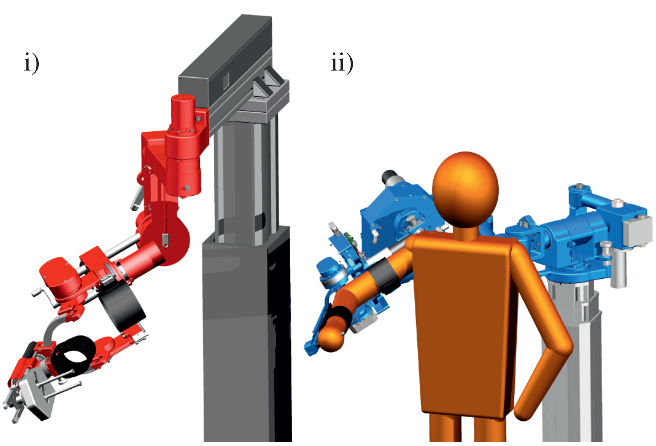

Fig. 1. The two arm exoskeletons i) ARMin and ii) ChARMin (shown with a simplified body model of a 13-year-old child).

III. Methods

A. General Design

The ChARMin robot consists of a proximal part (Fig. 2, left) that can be used for the whole target group from 5 years and older. The distal part can be exchanged according to the patient's age and arm size. The smaller distal module covers a range from approximately 5- to 13-year-old children, while a second module can be used for children aged 13 years and older. This modular design allows to have an exoskeleton that fits the patients needs better in terms of size and torques that can be applied.

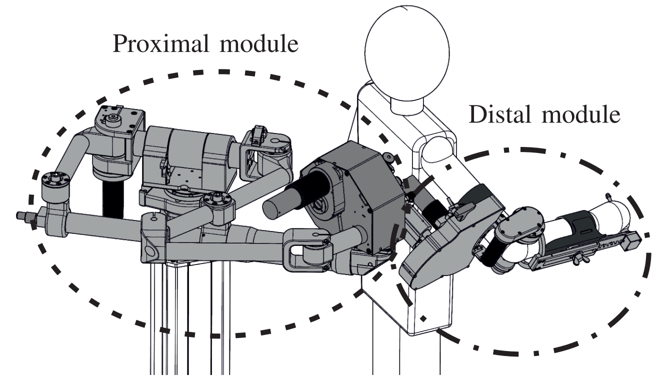

Fig. 2. Modular design of ChARMin with the distal module for younger patients, shown with a simplified body model of a 13-year-old child.

B. Joints and Kinematics

The first prototype of ChARMin has four DoF. The first axis of the robot actuates the horizontal shoulder ab-/adduction. The requirement to position the actuator sufficiently far away from the head of the child resulted in a parallel kinematics structure, in contrast to the serial kinematic structure used in the ARMin robot (Fig. 1, left). A simplified model of this remote center of rotation (RCoR) kinematics can be seen in Fig. 3. This RCoR allows to actuate the robot in a remote center (mot_1) and transferring the torque to the glenohumeral joint (GHJ) of the shoulder. An offset angle θ allows to optimally set the kinematic range of the robot to the functional RoM of the patient.

The second axis mot_2 actuates the shoulder flexion and extension. An offset Δd was introduced between the GHJ of the shoulder and axis mot_2 (Fig. 3) to account for the vertical translation of the GHJ. This configuration enables a vertical movement of the GHJ joint depending on the flexion/extension angle of the shoulder and following a circular segment [16].

The third axis mot_3 actuates the shoulder internal/external rotation (Fig. 5). Again, a parallel RCoR mechanism was applied to reduce static friction and to be able to bring the

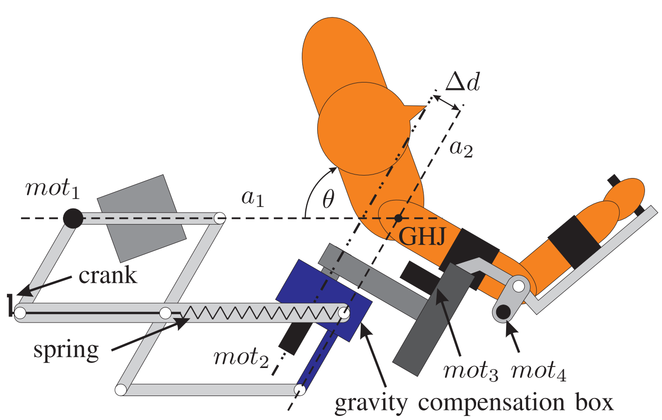

Fig. 3. Simplified representation of the remote center of rotation mechanism for the horizontal shoulder ab-/adduction (top view) [13].

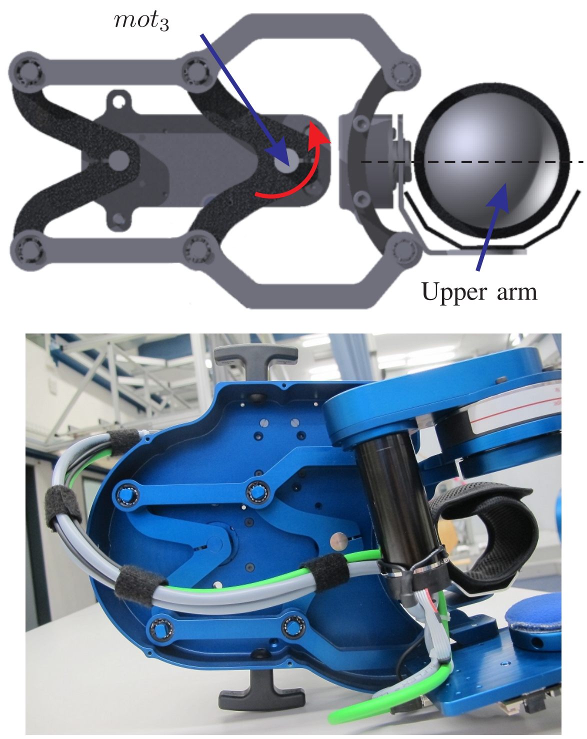

Fig. 5. ChARMin axis for the internal/external rotation of the shoulder (Kinematics by Stienen et al. [18]). Top: Technical drawing of the RCoR concept, Bottom: Parallel kinematics embedded in the robot.

patient's arm closer to its body without risking a collision between the robot and the trunk of the patient. This parallel structure was originally introduced by Stienen et al. [18].

The fourth actuated joint in ChARMin is the elbow axis mot_4. The actuator axis is arranged parallel to the human elbow joint axis (Fig. 3) and the transmission between the axes is done via a belt. The more distal joints are not actuated in this first prototype. A length-adaptable arm rest with a cuff for the forearm is provided as well as an exchangeable rubber bulb that can be grabbed by the child.

C. Gravity Compensation of the Robot

In order to achieve a passive gravity compensation of the robot, a spring mechanism is included in axis 2 of the proximal module (compensation box in Fig. 3). A spring S is attached in an offset distance d_s to the rotation shaft C (Fig. 4) using a rope that is deflected by different small pulleys A. This spring is integrated in the parallel RCoR structure (indicated with a zigzag line in Fig. 3). This spring arrangement produces a maximum torque when the robot arm is horizontal, whereas it has no effect, when the robot arm points up- or downwards. To account for the different distal modules, the spring pretension can be changed by means of a crank (Fig. 3).

D. Change-of-Side Mechanism

To enable left and right arm training a new change-of-side mechanism was developed. In order to change the side configuration, the whole exoskeleton can be rotated around the horizontal axis a_1 (Fig. 3) and the angle θ changed accordingly. As a consequence, the passive gravity compensation applies the offset torque in the wrong direction. Therefore, in a second step, the gravity compensation has to be changed in order to invert the passive compensation. This is done by means of a novel passive toggling mechanism located in the compensation box (Fig. 4) [13].

E. Adjusting the Robot to the Patient

In order to avoid unwanted interaction torques coming from a misalignment between the robot axes and the anatomical joints, the robot has to be optimally adjusted to the patient's arm. This can be achieved by length adaptation mechanisms for the upper arm and forearm and by cuffs with changeable circumferences. The positioning of the shoulder is simplified with two switchable laser pointing to the GHJ of the patient along the axes a_1 and a_2 (Fig. 3). The positioning is done by adapting the height of the lifting column in the back of the robot and wheels that allow to move the robot relatively to the patient.

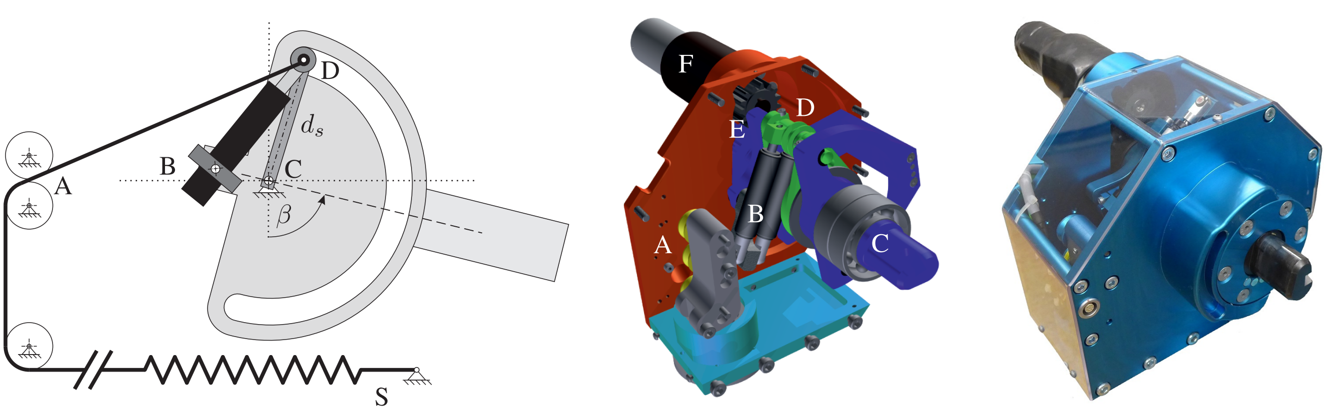

Fig. 4. Passive gravity compensation with a toggling mechanism for changing the direction of the compensation torque. Left: Simplified representation of the mechanism with the deflection pulleys (A), dampers to decelerate the toggling mechanism (B), axis 2 (C), offset attachment point for the rope (D) and the spring (S) [13]; Middle: Technical design of the mechanism with the custom gear (E) and the motor with gear (F); Right: Finished hardware.

TABLE I

ACTUATION, TRANSMISSION AND NOMINAL TORQUES FOR THE FIRST FOUR AXIS OF THE CHARMIN ROBOT FOR THE SMALL DISTAL MODULE.

Axis	Joint	Motor	Gear	Ratio	Nominal torque
1	Shoulder horizontal add-/abduction	Maxon RE40	Harmonic Drive, CSG-17-120	1:120	18.0 Nm
2	Shoulder extension/flexion	Maxon RE40	Custom gear and Maxon planetary gear, GP 52C	1:162	22.7 Nm
3	Shoulder internal/external rotation	Maxon RE35	Maxon planetary gear, GP 42C	1:113	8.6 Nm
4	Elbow extension/flexion	Maxon RE30	Harmonic Drive, HFUS-14-100	1:101	6.3 Nm

F. Actuation

The exoskeleton is actuated with electric Maxon DC motors in combination with either harmonic drives or planetary gears. The first two actuators are on the proximal robot module and are, therefore, identical for the whole age range. However, the motors on the distal part are being exchanged together with the distal module. The different actuator-transmission combinations and the corresponding nominal torques can be found in Tab. I. The values listed are for the robot equipped with the smaller distal module for children aged 5 to 13 years, which corresponds to the current hardware.

G. Electronics and Control

The control strategy for the robot is implemented in MATLAB/Simulink and is executed on a PC system using the xPC target real-time environment (MathWorks). Currently, a path controller is used to assist the patient's arm during point-to-point movements [19]. The control system is running at 500 Hz. The inner loop of the path controller is a current controller which is directly located on the motor drive. In previous robot control setups all the motor drives were located in the back of the robot (similar to Fig. 7, bottom left). This led to a lot of cables reaching from the back of the robot to the motors, encoders and potentiometers of each of the joints. Since the new ChARMin setup is modular and has an exchangeable distal part it is important to reduce this cabling, as the cables need to be unplugged each time the module is exchanged. Furthermore, it is known that cables have an influence on the robot joint dynamics [20]. This influence is usually nonlinear and can vary over time and is, therefore, rather difficult to model. In the ChARMin robot, a different approach was taken, where the motor drives for the distal part are located directly on the exoskeleton close to the actuator.

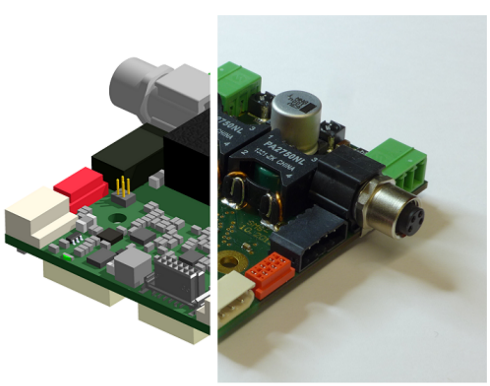

Fig. 6. Technical drawing (left) and the finished hardware (right) of the newly developed axis controller boards used on the distal part of the robot for current control of the actuator and reading sensor information.

Each of these 'axis controllers' (Fig. 6) encompasses the current controllers for two actuators as well as two encoder inputs, two digital outputs, a digital input and three analog inputs. The communication between the boards and the real-time system is implemented using a CAN 2.0 B interface. Having these axis controllers, the cabling is reduced to a power cable and a cable for the CAN bus communication. The axis controller boards were developed and built in-house and are very small in size (52x63x18 mm). More technical details about the axis current control boards can be found in Tab. II.

TABLE II

TECHNICAL SPECIFICATION OF THE CHARMIN AXIS CURRENT CONTROL BOARDS

Board interface	
Board supply voltage	48 V
Communication	CAN 2.0 B
Transfer rate	1 Mbit/s
Motor interface	
Max output current	5.5 A
Output voltage	-48 ... +48 V
Sample rate current controller	22.05 kS/s
Encoder input	20 bit
Optional I/O's	
3 Analog inputs	10 bit
1 Digital input	5 V TTL
2 Digital outputs	5 V TTL

IV. RESULTS

The hardware for the first ChARMin prototype with four DoF was recently finished (Fig. 7). With its modular design the exoskeleton covers the range from 5 to 18-year-old children suffering from CP, according to the above mentioned requirement (Req. a). Moreover, the different robot segment lengths for the upper arm, forearm and hand are adjustable in length and the cuff circumference can be adapted to the patient's arm (Req. b). The actuation of the robot (Tab. I) was chosen using norm data from the literature for healthy children. The achievable nominal torques are lower than the maximum force that a child can apply (Req. c). The RoM of the robot joints covers most of the given RoM for activities of daily living (Tab. III) (Req. d). However, in direction of the shoulder extension and internal rotation the range was reduced using mechanical end stops to avoid collisions with the sitting patient. The robot is mobile with lockable wheels. A change-of-side mechanism was realized by flipping the

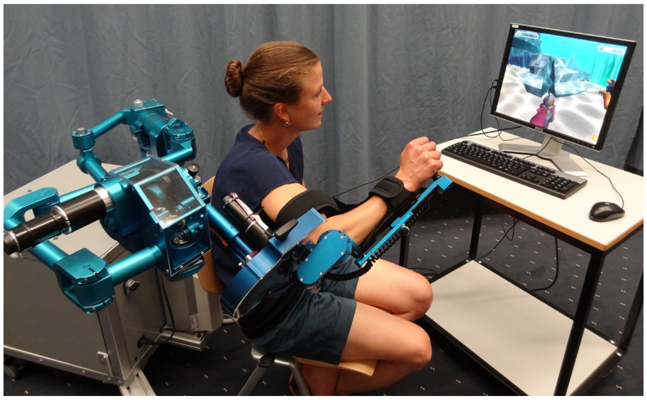

Fig. 7. First ChARMin prototype with four DoF and a healthy subject. The picture shows a possible setup with the audio-visual display for the therapy. The axis control boards are not mounted in the picture.

TABLE III
ACHIEVABLE JOINT ROM OF CHARMIN

Robot axis	Corresponding joint	Min. angle [°]	Max. angle [°]
Axis 1	Shoulder horizontal add-/abduction	-10	95
Axis 2	Shoulder extension/flexion	50	130
Axis 3	Shoulder internal-/external rotation	-30	70
Axis 4	Elbow extension/flexion	0	120

whole robot over around its horizontal axis (Req. e). The RCoR mechanism increases the distance between the robot and the head of the patient (Req. f). The static friction of the joints is given in Tab. IV. The breakaway torque was measured with an externally applied force sensor, type 9205, KISTLER, Switzerland. All the joints are backdrivable. The inertia for the 4 joints is given in Tab. IV. The joint inertia is the sum of the link inertia and the reflected actuator's inertia and is estimated from the robot CAD model with the robot length settings in the middle of the adjustable range. Further requirements for safety were addressed with the mechanical gravity compensation which is achieved with a passive spring mechanism that can be used for both arm configurations by means of a mechanical toggling mechanism. Furthermore, mechanical end stops are provided for all joints. Finally, along with the robot, a game-based VR interface is being developed that can be used for pediatric rehabilitation to promote an active participation of the child (indicated in Fig. 7, right) (Req. g).
As a first evaluation of the control performance, the position control bandwidth was measured for each joint with a constant sinus amplitude of 5 °. The bandwidths are 2.1 Hz, 3.0 Hz, 5.3 Hz and 5.5 Hz for the axes 1 to 4, respectively.

V. DISCUSSION

The presented design of ChARMin has four DoF and was developed according to the clinical and technical requirements described in this paper. Different challenges evolved from the requirements and were addressed in the robot

TABLE IV
STICTION AND JOINT INERTIA OF THE CHARMIN JOINTS

Robot axis	Corresponding joint	Static friction	Joint inertia
Axis 1	Shoulder horizontal add-/abduction	1.6 Nm	2.45 kg·m^2
Axis 2	Shoulder extension/flexion	3.0 Nm	0.82 kg·m^2
Axis 3	Shoulder internal/external rotation	0.6 Nm	0.11 kg·m^2
Axis 4	Elbow extension/flexion	0.5 Nm	0.06 kg·m^2

design. The exoskeleton can be used for rehabilitation of children aged 5 to 18 years by means of a modular and adjustable design that covers the anthropometric needs of the target group. It needs to be tested whether the safety-related reduction in RoM (shoulder extension and internal rotation) is restricting the child when performing arm movements.
While the static friction in axis 3 and 4 is low, the static friction in axis 1 and 2 may need to be further decreased. Different approaches are currently being evaluated. Possible solutions are the use of force/torque sensors on the exoskeleton or a feed forward dithering signal for the actuator for small angular speeds of the robot.
The nominal torque of the motors is less than the maximum torque that a strong patient may be able to apply temporarily. However, the motor can be overloaded by the drive for a short time to produce up to five times the nominal torque to resist the arm when needed, e.g. during an isometric force measurement. For this load condition a thermal model needs to be derived to observe the winding temperature.
Furthermore, the handling of the change-of-side mechanism as well as the exchange of the distal module (weight: 5.7 kg) requires some practice and has to be tested with the therapist in the clinical environment.

VI. CONCLUSION AND OUTLOOK

In this paper, we showed how the challenges given by the pediatric target group influenced the geometric design, the kinematics, the actuation, the electronics and the implemented safety features in the ChARMin robot. To our knowledge, ChARMin is the first active exoskeleton robot that was specifically built for pediatric arm rehabilitation.
First feasibility tests and clinical trials will be performed in the Rehabilitation Center for children and juveniles, Affoltern am Albis, Switzerland, after all ethical and regulatory issues have been taken care of. In near future, the distal DoF for pro-/supination of the forearm and wrist extension/flexion are going to be added and, therefore, the robot will be extended to 6 DoF.

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