Performing Activities of Daily Living with a Fully Actuated 9-DOF Shoulder and Arm Exoskeleton

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***Abstract*— We developed a fully actuated exoskeleton that covered all nine relevant degrees of freedom of the human arm while providing enough range of motion, speed, strength, and haptic-rendering function to provide meaningful neurorehabilitation therapy to severely and mildly affected patients. The unique kinematic structure of the robot and the large impedance bandwidth of haptic rendering allowed training for most activities of daily living with real or virtual objects. Thus, next to neurorehabilitation, this robot could find an application in testing different actuation and control methods (*e.g.*, actuation synergies) for evaluation of portable assistive robot concepts. Further, potential application fields are in telemanipulation, and as a haptic-device for entertainment applications.**

I. Introduction

Therapy robots have the potential to substitute the physical interaction and complement the decision-making processes that therapists perform during conventional therapy. Thereby, therapists could employ their expertise more effectively without getting distracted by repetitive physical interactions and cognitively simple tasks. Thereby, the labor cost per provided therapy can be reduced while leveraging the benefits of data-driven intervention, gamification, and the high amount of repetition that the robots can offer. To maximize impact in clinical application, robots should be able to support these aspects while being applicable to provide a versatile range of neurotherapy exercises for a diverse variety of patients [1], [2]. However, state of the art rehabilitation robots either lack the range of motion (ROM) or the speed to provide meaningful therapy to mildly affected patients (*e.g.*, ARMin III [3]) or do only provide restricted support and no guidance, *e.g.*, passive devices with anti-gravity support only. Hence, we developed ANYexo 2.0, a fully actuated, torque-controlled upper-limb exoskeleton including all nine relevant degrees of freedom of the human shoulder and arm (see Fig. 1).

II. Robot Design

We chose an exoskeleton structure to achieve full control and observability over all arm segments with minimum actuation and small footprint. The human upper limb comprises nine relevant degrees of freedom (DOF): a 2-DOF sternoclavicular joint (SC), a 3-DOF glenohumeral joint (GH), a 1-DOF elbow joint (EB), and a 3-DOF wrist (WR). The kinematic structure of ANYexo comprises the same joint groups (see Fig. 2). The kinematic structure of the shoulder was designed to replicate the dexterity of the human shoulder with a focus on the range of motion required for activities of daily living. The shoulder kinematic structure, together with the elbow, was presented in [4]. We extended this structure with a spherical wrist joint consisting of three rotational joints. Series-elastic actuators drove the SC and GH joints with $77\,\mathrm{N\,m}$ peak torque. The elbow and wrist joints had $39\,\mathrm{N\,m}$ and $23\,\mathrm{N\,m}$ peak torque, respectively. For the wrist, pseudo-direct drives with a gear ratio of 1:8 were used. The speed provided by the actuators sufficed to perform movements with velocities around twice as high as required in activities of daily living [5]. The SC joints were coupled to the plane of elevation and angle of elevation (*i.e.*, humerothoracic elevation) of the upper arm by an impedance controller. The neutral position of the impedance controller mimicked the physiological shoulder synchronization.

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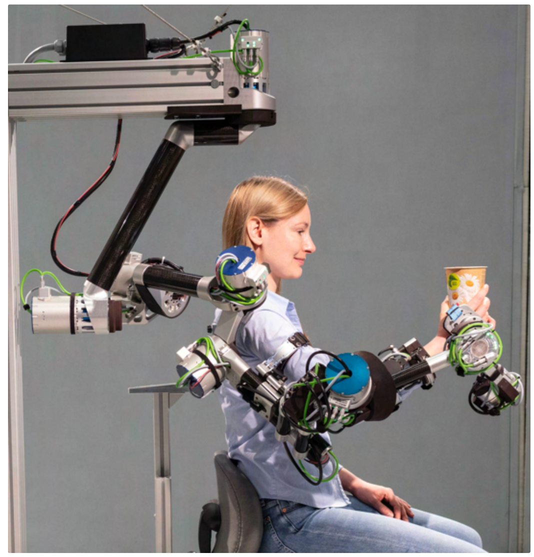

Fig. 1. ANYexo with a user in interaction with an object.

III. Experiments & Results

The range of motion of the robot was evaluated using a grid search for the coupled shoulder and wrist poses. The simulated robot was controlled to drive to all eligible joint positions in a physics simulation. Thereby, we assured that the joint group poses were not only possible but also reachable (see Fig. 3). In addition, a user without impairments performed a couple of ADL while being attached to the robot. The robot was controlled to behave haptically transparent (see Fig. 3a).

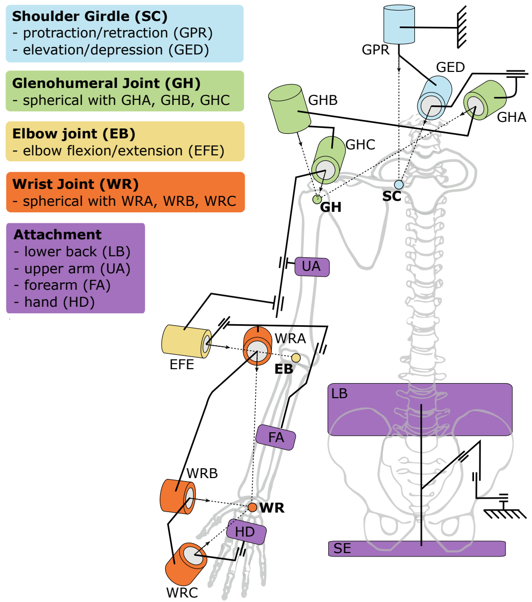

Fig. 2. Kinematic structure of ANYexo.

IV. Discussion & Conclusion

The ROM of the robot suffices to cover the ROM required for ADL as reported by [6], [7]. By performing some ADL with the robot, we could demonstrate that the coupled human-robot system can also reach the required ROM. The speed of the actuators allows training ADL at the regular speed of people without impairment [5] and even higher. The unique kinematic structure, link design, and attachment concept of the robot allowed interaction with real objects and the user's own body. Thus, users can perform or train upper limb ADL with ANYexo with only minor restrictions. The robot's strength and precise joint torque control allow it to support, guide or resist the user's movements. The robot's strength even allows maximum isometric strength training of the shoulder and wrist for the average human. The presented exoskeleton is the first to cover all relevant nine DOF of the human shoulder and arm with fully actuated joints and sufficient power for versatile training of a broad spectrum of patients. This ability widens the applicability of powered rehabilitation exoskeletons to users with minor impairment. Further, due to the improved skills in speed and ROM, the ANYexo could be used to evaluate assistance force profile concepts for developing hardware and controls of wearable assistive devices, *e.g.*, exomuscles.

V. Acknowledgement

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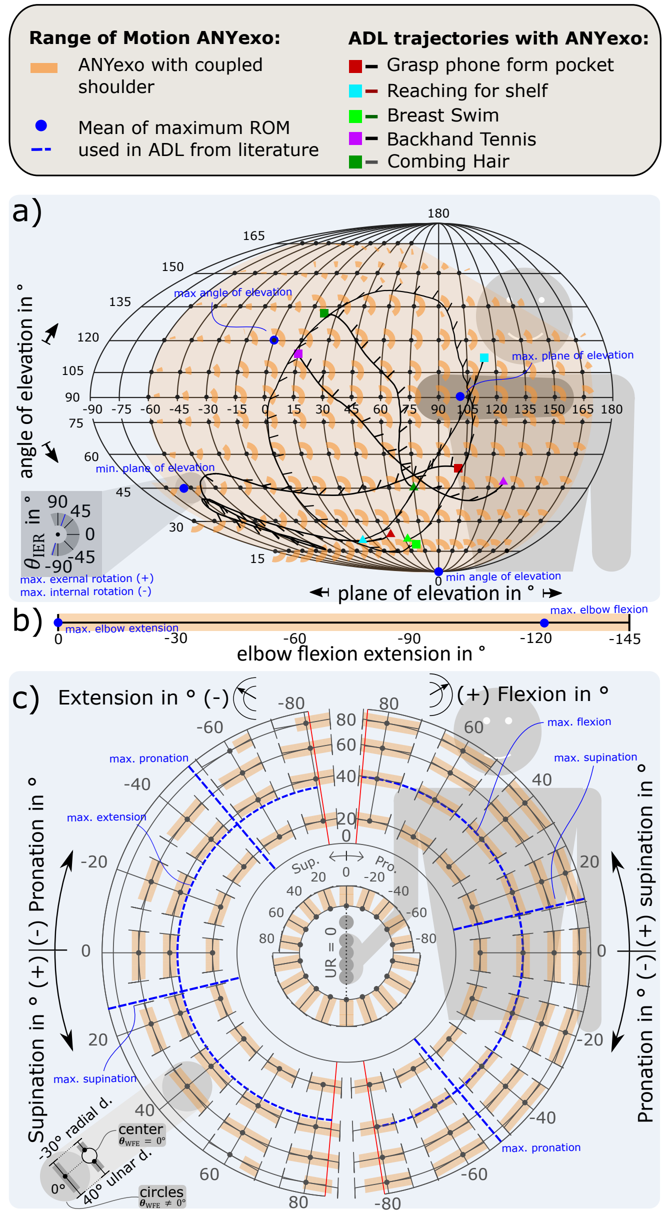

Fig. 3. Range of motion of ANYexo compared to the range of motion required for ADL reported by related work (shoulder [6], wrist [7]) and trajectories of ADL movements of a user with the ANYexo. a) shoulder; b) elbow; c) wrist.

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