Research on Exoskeletons at the TU Berlin

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Abstract We present an overview of the work devoted to exoskeletons which has been performed for the last seven years at TU Berlin. Three different types of exoskeleton devices have been developed: hand and finger exoskeletons for rehabilitation, a leg exoskeleton for motion support, and an arm exoskeleton for multimodal human-computer interaction. The research has been focused on different types of control strategies and algorithms as well as on the implementation of applications. The main part of this work is devoted to using electrical muscle signals for the control systems. We present the concepts for design and application, review the main algorithms and show experimental results and first experience with applications.

1 Introduction

Exoskeletons are actuated mechanical constructions attached to the human body. The possibility to influence the human motion makes this kind of robots fascinating research objects with a huge potential for practical applications. The range of possible applications is wide: motion of human limbs along predefined trajectories (e.g. locomotion of fully paralyzed patients), pure force enhancement, intelligent assistant (e.g. assembly assistance) as well as immersion into virtual reality [16, 5, 13, 21].

The level of control intelligence required for an exoskeleton for the above mentioned applications is very high: Due to the direct contact between the mechanical construction and the human body the system should have the same level of ”motion intelligence” as the human. Therefore, the development of a universal controller for such devices is difficult due to lack of basic approaches. Even the control along fixed predefined trajectories is complicated because human limbs have to be modelled if

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a high performance control with high gains is required. Furthermore, mechanical constructions become complicated for non-restricted applications (support for the whole body). The realistic approach to further developments is to choose particular applications and to develop specialized mechanical constructions and controllers. Most controllers for clinical applications are based on the evaluation of muscle signals to incorporate human activity directly into the control loop with different approaches on how to evaluate those signals [2, 4, 11, 29]. Most other applications (e.g. force support for factory workers, rescue teams, soldiers) use dynamic models of interaction forces [12, 20] or input from additional devices and sensors [17].

For our research three fields of application were chosen: a hand exoskeleton for rehabilitation support after hand surgeries, a leg exoskeleton with an actuated knee joint for support/force enhancement and an arm exoskeleton to be used as a haptic device with a large workspace for immersion into virtual reality. We have laid the focus on the development of the controllers and have chosen constructions with some restrictions on the human motion to be able to assemble the devices in a short time and at moderate costs. Despite the motion limitations the constructions allow us to investigate the desired applications without considerable drawbacks.

The paper is organized as follows: In section 2 the hand exoskeleton for rehabilitation support after hand surgeries is presented. The purpose of this device is to move the fingers of a patient in order to restore motor capabilities of the hand after surgery and to avoid post-surgery complications. One important issue of the controller development was the realization of high gains in a system with unknown variable parameters and big unmodelled disturbances caused by human interaction. The successfully realized approach is based on the application of sliding-mode control. In section 3 the exoskeleton for the lower extremities with an actuated knee joint is presented. This device is supposed to be used for force enhancement of elderly or support for disabled people. The research with this device was focused on the application of electrical muscle signals (EMG) for control. The main issue of the realized controller was the usage of those signals directly in the control loop to allow flexible and spontaneous movements. In section 4 a perspective on the ongoing work related to the arm exoskeleton for immersion into virtual reality with haptic feedback is presented. In section 5 the work is concluded.

2 Exoskeletons for the Hand

Two devices were developed. Both were designed with the focus on the support of rehabilitation and diagnostics after hand surgeries or strokes. The first device – the hand exoskeleton – is equipped with many sensors and utilizes a complex linkage to exert forces on joints of the hand. It was mainly used for the development of control algorithms. The second device – called finger exoskeleton – supports only a single finger, but features an improved mechanical construction and was developed with focus on safety and usability during clinical trials. Figure 1 shows both devices.

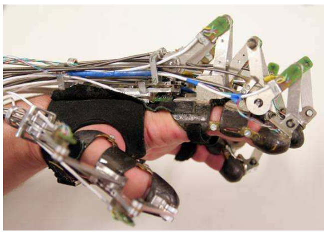 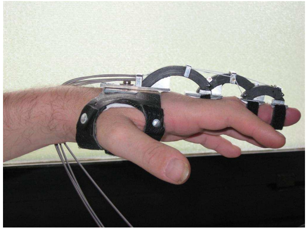

Fig. 1 Developed exoskeleton devices. Left: hand exoskeleton with 20 degrees of freedom. Right: finger exoskeleton with improved mechanical construction and 3 degrees of freedom.

2.1 The Hand Exoskeleton

The hand exoskeleton supports flexion, extension, abduction and adduction of all major joints of each finger, resulting in 20 supported degrees of freedom. The palm is free of mechanical elements to allow interaction with the environment. The fingers are moved by a construction of levers actuated through pull cables guided by flexible sheaths and driven by DC motors. Pulleys at the levers allow bidirectional movement. Finger joint angles are measured by Hall sensors which are integrated into the mechanical construction. Angles of the axes at the motor units measured by optical encoders correspond to the angles measured by the Hall sensors. Because of varying tension in the connecting cables both values for joint angles deviate. Five force sensors integrated between the levers and finger attachments measure forces during flexion and extension at the finger tip. Surface EMG electrodes measure muscle activity at ten locations at the forearm.

2.2 The Finger Exoskeleton

The finger exoskeleton supports three degrees of freedom for one finger with a range of motion of 90 degrees for the proximal finger joints. The improved mechanics with circular arc joint is more compact and allows a smooth and ergonomic movement of the finger without additional supporting joints at the sides of the finger joints. The device was designed with the focus on reliability and safety for the use during clinical trials. The safety measures include a medical power supply, slip clutches to limit the motor torque and a watchdog monitoring the microcontroller responsible for the control loop. The safety of the system is certified and clinical trials are scheduled.

The circular arc joint joints are composed of several arcs which can move against each other. They work similar to a telescopic joint with the difference that the guide is along a circular arc and not along a line. The arc joint is placed above the finger joint so that the center point of the circular arc is in one place with the revolving joint of the finger. The movement of the joint occurs in both directions by using a cable driven mechanism with two cables. When combining three circular joints for the finger exoskeleton, it is possible to get along with four pull cables, similar as for the human hand: one for extension and three for the flexion.

Compared to others, this construction is simple and robust. A similar construction was used for the proximal joint force support for an extravehicular glove [28]. In contrast to us they utilize an ultrasonic motor attached to the hand base which moves a steel belt along a circular guide. But by using our cable driven construction it becomes possible to use other actuators and control the distal joints.

2.3 Control Methods for the Hand and Finger Exoskeletons

The hand exoskeleton supports three control modes: trajectory control, force control, and EMG control. Due to the lack of sensors the finger exoskeleton supports only trajectory control. The first control mode allows following trajectories determined by the therapist. This allows repeating exercises reliably with a high accuracy. The challenge was here to achieve the required motion accuracy despite strong disturbances caused by patient interaction. The developed controller was based on application of a sliding-mode high gain controller described in [15]. The second control mode uses force sensors to determine the motion of the exoskeleton. The force control uses force sensor readings to calculate the desired motion with an open-loop admittance control scheme. During this control mode the exoskeleton follows the motions of the hand. But the force sensors cannot distinguish between internal and external contact forces. Therefore, they are insufficient to measure the human motion intention during contact with the environment (e.g. grasping), which is common during rehabilitation. Integrating more force sensors to distinguish between internal and external is not practicable for the hand exoskeleton due to the constricted space. Details of construction, sensors and control algorithms are described in [26].

Details: EMG Control for the Hand Exoskeleton

EMG sensor data can be used to control the hand exoskeleton. Those signals represent the human intention better than using only force sensors. However, there are several difficulties in their application. One problem is that only a subset of all muscles responsible for the hand motion can be measured by surface EMG sensors. Therefore, it is not possible to use the EMG signals alone to control arbitrary motions in all supported degrees of freedom. Force contributions of muscles that are not measured are derived from the other muscle signals by assuming a specific hand movement. The second problem is that captured EMG signals are superimposed by the signals of nearby muscles. This problem can be reduced by utilizing blind source separation algorithms. Figure 2 depicts the several computing steps of the EMG control scheme used for the hand exoskeleton.

Due to the limitation of space only the extrinsic muscles of the forearm are measured. The following sensor locations were selected for measurement: *M. flexor dig-*

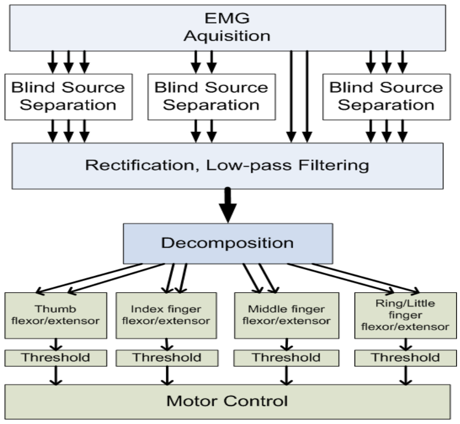

Fig. 2 Scheme of the EMG control for the hand exoskeleton device. After EMG signal acquisition blind source separation is used to partially separate the superimposed EMG signals. After rectification and low-pass filtering an additional decomposition step is used to assign the signals to different degrees of freedom. After applying a threshold the signals are translated to forces which are used to generate a trajectory executed by the underlying position control.

itorum superficialis near wrist (two electrodes), *M. flexor policis longus* (one electrode), *M. flexor digitorum superficialis* middle section of forearm (one electrode), *and M. flexor digitorum superficialis* upper section of forearm (one electrode) at the palmar side. *M. Extensor digitorum* (three electrodes), *M. Extensor pollicis longus* (one electrode), *and M. Extensor indicis* (one electrode) at the dorsal side.

The blind source separation algorithm used was chosen for low latency, to prevent problematic delays. The signals are filtered by a weighted low-pass differential filter. The inverse demixing matrix is then approximated by an iterative algorithm described in [10] (EASI). By using these algorithms a separation of about 1.5dB for neighboring sensors can be achieved. After the blind source separation the signals are still partially superimposed.

Additional filtering steps are: rectification, low-pass filtering and another decomposition step. This step is implemented to achieve muscle signal decomposition for the different degrees of freedom. The goal is to achieve a one degree of freedom control for each finger. To accomplish this a single extensor and flexor signal for each degree of freedom are separated by a simple linear demixing algorithm. During calibration several movements for each finger have to be performed to determine a demixing matrix. During early experiments it turned out, that it is problematic to separate the muscle signals from the ring and little finger: therefore movement of these fingers is expected to be coupled. Another limitation is that the wrist should not be moved as the muscle signals change for different hand postures.

As only a few muscles responsible for the motions of the hand are measured an accurate biomechanical model to translate the muscle activation signals is not possible. Instead a very simple model is implemented, where each finger is in its relaxed position when no muscle activation is measured. Depending on the muscle activation a linear force is calculated and the fingers are moved as if acting against a constant friction. The generated trajectory is then executed by the underlying position controller which is based on sliding mode control and therefore very robust for parameter variations and varying loads. By using the EMG control algorithm it was possible to control the hand exoskeleton in four degrees of freedom, more details and results of this algorithms are shown in [27].

3 Lower Extremities

The focus of the research with the lower extremity exoskeleton is to investigate control schemes which allow the exoskeleton to recognize and support the intended movements of the operator. The human-machine interfaces which the schemes depend on are designed to cope with the abilities and limitations of certain categories of users. We have investigated the following schemes:

1. The *torque amplifying scheme* evaluates muscle activities of the operator and adds a linear amount of torque to the supported joint through the actuator. The main means of information transportation are electrical muscle signals (EMG).
2. The *model-based approach* is designed to allow the system to control the postural stability of the operator with the exoskeleton. The interface is based on evaluation of muscle signals and information about the movement, posture and environment.

The exoskeleton used for those experiments covers thigh, shank, and foot of the right leg (refer to figure 3). The knee joint is driven by a linear actuator consisting of a DC motor and a ball-screw. The ratio of the transmission is chosen in such a way that the power is sufficient to give support with up to 150Nm in the knee joint and allows slow walking [6]. Six electrodes are embedded in the thigh brace and record signals from knee flexor and extensor muscles from the skin. Those signals together with the knee angle are sent to a single board computer which the operator is carrying on his back. All signals are digitized with 1kHz and downsampled to 100Hz for model computation. The resulting values are passed to a low-level control loop which runs with 1kHz to provide sufficient control signals for the actuation.

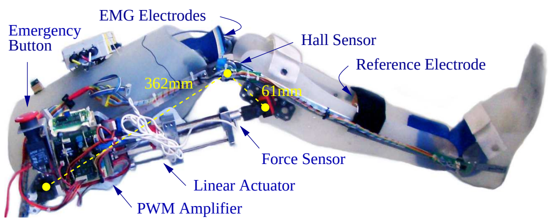

Fig. 3 Leg exoskeleton (without the portable PC): The knee joint is driven by a linear actuator. Knee and ankle angles are measured with Hall sensors and EMG sensors are embedded in the thigh brace to measure muscle activity.

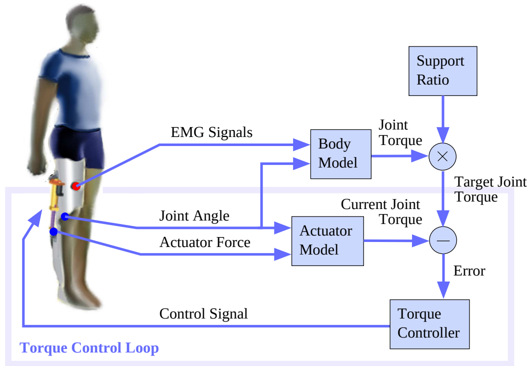

Fig. 4 The EMG signals are recorded with electrodes attached to the thigh and are evaluated through a body model that computes an estimate of the operator's torque contribution. The result is multiplied by a support ratio and passed to the torque controller that sets the signals for the actuator appropriately. This system acts as an amplifier of the operator's torque.

3.1 EMG-based Torque Amplifier

This control scheme is based on the evaluation of electrical signals which are emitted by the muscles upon their activation as shown in figure 4: Inside the body model a Hill-type muscle model derives the neural activation of the muscle from its EMG signal, converts this activation into a muscle fiber force and finally into the torque the muscle is producing around the knee joint [8]. Among other details, this muscle model includes the computation of the neural activation based on [23], the active and passive force components as a function of the muscle fiber length and the muscle and tendon pathway along the skeleton as described in [30, 3]. This is performed for all six recorded muscles. The resulting sum of the torques gives an estimation of the operator's own torque contribution to the movement. This value is multiplied by a support ratio and used as the target value for the PID torque controller of the actuator.

In addition to the control scheme, we have developed a new calibration algorithm for the model parameters which is described in detail in [6]. This calibration has to be performed whenever the exoskeleton is put on, because some characteristics of the operator depend on the current body state (e.g. moisture on skin).

The *torque amplifying scheme* puts the user in full control of the exoskeleton, allows flexible movements and spontaneous reactions to circumstances in the real world. But the user has to be able to react to the movement that results from the combined effort of his / her own muscles and the actuator torques in a coordinated manner. The operator has to be in full control of his / her own muscles, although they may be too weak to fulfill the intended task. Intended applications are for example: carrying aids for factory workers or force support for elderly people.

3.2 Model-based Controller

This approach is based on computation of a rigid body model of the human with two legs and a torso. The joint angles and velocities of the corresponding limbs are measured with the aid of a second, light-weight orthosis for the other leg and the torso. The sensor values are fed into the inverse computation of the model which gives an estimate of the torques the operator is producing with his muscles in the joints, except for the supported knee joint where the movement is defined through the actuator. In this joint, the torque of the operator is derived from EMG signals [7]. The

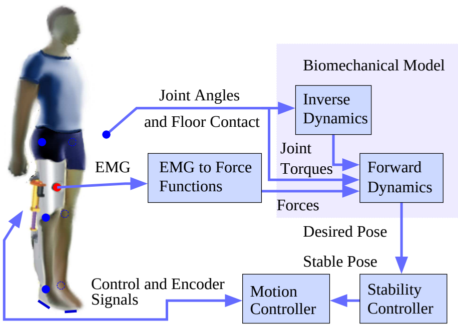

Fig. 5 The model-based control scheme: The biomechanical model predicts the motion by evaluating the movement and muscle activity of the operator. This prediction is modified to ensure postural stability before the result is passed to the PID position controller of the actuation.

biomechanical model then predicts the movement that will result in the next period of time (10–20ms in advance, refer to figure 5). The stability controller [14] applies torques to the joints so that the zero moment point does not leave the footprint of the operator's foot that has floor contact (similar to control of biped walking robots).

The focus of the *model-based approach* is to give support to extremely handicapped people who are not able to balance themselves, but have a certain degree of control over their own limbs. The exoskeleton should be used during rehabilitation or at home. While it is not possible to control postural stability with an exoskeleton that supports only the knee joint, this algorithm nevertheless gives interesting insights in problems related to this approach.

3.3 Experiments and Discussion

The most successful experiments have been performed with the *force amplifying* scheme. For the first time, a lower extremity exoskeleton has been controlled with a sophisticated biomechanical model evaluating EMG signals which fuses results from different international research groups. Such an experiment is shown in figure 6, where the stair climbing movement is supported with a ratio of 0.5. It can be seen that the resulting movement is smooth while the exoskeleton is contributing a significant amount of torque. More experiments are presented in detail in [6, 8].

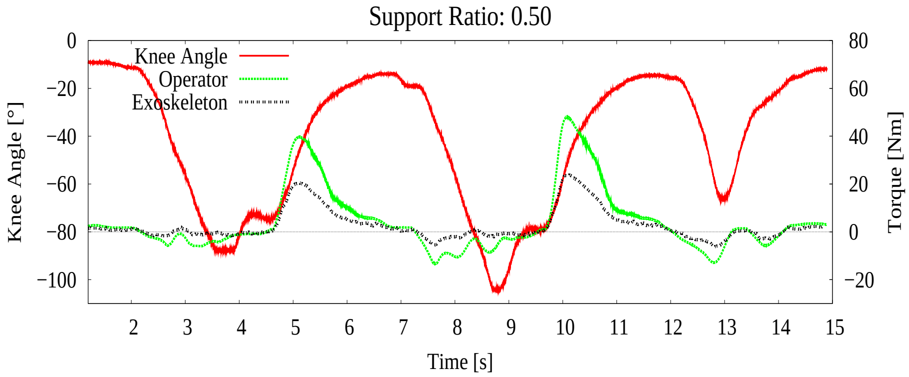

Fig. 6 Stair climbing experiment with a support ratio of 0.5: The movement can be performed smoothly and the actuator contributes half of the estimated operator's torque (0°: straight leg, negative angles: knee flexion). At $t \approx 3.8$s the foot is raised over the first step and at $t \approx 4.5$s lowered onto this step. After that the not-supported leg climbs the second step and at $t \approx 8.8$s the foot of the supported leg is raised over the third step, before it is put down again at $t \approx 9.5$s.

The *model-based approach* revealed some fundamental problems which could not be solved up to now: The model prediction is too inaccurate to allow the actuator to contribute significant amounts of torque in a robust manner, preventing similar real-life experiments as detailed in [7]. A much more complex sensor setup with information about the operator and the environment would be necessary but this contradicts the idea of a flexible and mobile system.

4 Work in Progress: Arm exoskeletons for multimodal human-computer interaction

The ongoing work in our laboratory for multimodal human-computer interaction is focused on the development of a system for virtual reality with haptic feedback based on light weight arm exoskeletons. The key features of this system are a high degree of immersion into the computer generated virtual environment and a large working volume. Existing solutions for mobile haptic displays combine a grounded haptic device like the Sensable Phantom with a mobile robotic platform and control strategies to place the platform in an optimal manner to the user in order to maximize the workspace. These solutions suffer of drawbacks like the limited reactiontime and speed of the mobile platform and the control strategies [22, 9]. Our approach aims at a wearable haptic device and thus avoids these drawbacks. The high degree of immersion will be achieved by multimodal human-exoskeleton interaction based on haptic effects, audio and three dimensional visualization. The large working volume will be achieved by a lightweight wearable construction which can be carried on the back of the user. The first prototype of the mechanical construction is shown in figure 7.

Fig. 7 First prototype for arm exoskeleton with three actuated degrees of freedom. The design objectives were: the reduction of the weight and increasing of the working volume.

By reducing the weight of the arm exoskeleton in order to make it wearable, the degree of stiffness of the mechanical constructions is getting limited. This will also limit the stiffness of the contact forces in the haptic modality. Due to the reduction of the devices weight it is also very difficult to actuate all degrees of freedom of human arm motion with a wearable mechanical construction. Therefore the arm exoskeleton will only have three actuated degrees of freedom. Lack of high stiffness as well as non-actuated degrees of freedom make it difficult to reproduce interactions with rigid objects in virtual environment realistically. The drawbacks of bad stiffness of a lightweight wearable mechanical construction can be compensated by elaborated control to some extent. The integration of additional actuated degrees of freedom into the exoskeleton arms would increase weight and reduce the working space of the mechanical construction.

In our research work we plan to achieve a compensation of the above mentioned drawbacks by utilizing the subjective perception of the user. Earlier research has shown that there is a great potential for this approach to improve the degree of immersion in a virtual environment [24, 19, 1, 25, 18]. The elaborated control of three actuated degrees of freedom in each arm should create the subjective feeling of high fidelity interaction. This interaction will be enriched by sound and visual effects. Development of algorithms for appropriate combination of these modalities for reproducing different interaction effects is the first of three main research fields of our laboratory for multimodal human-computer interaction. The second research field is related to the control of mechanical constructions with bad stiffness in haptic applications. Efficient algorithms for visualization, collision detection and force rendering in large three dimensional virtual environments is the third research field. The research conducted in these three fields is focusing on specific applications. At the moment we are developing particular effects for a game and for putting a virtual production line into operation.

5 Summary and Conclusion

During the last seven years we have performed research with promising results in the area of exoskeleton devices. Especially the developments for human assistance (load carrying, haptic guidance) and rehabilitation offer an interesting perspective for future research and applications.

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