Development and Control of a Hand Exoskeleton for Rehabilitation of Hand Injuries

Andreas Wege and Günter Hommel

Real-Time Systems and Robotics
Technische Universität Berlin
Berlin, Germany

{awege,hommel}@cs.tu-berlin.de

***Abstract* – Hand injuries are a frequent problem. The great amount of hand injuries is not only a problem for the affected people but economic consequences follow because rehabilitation takes a long time. Physical therapy after an operation is associated with high personnel expenses. To improve therapy results and reduce cost of rehabilitation a hand exoskeleton was developed. The hand exoskeleton was specifically designed to accomplish requirements of medical applications. For research on control algorithms and rehabilitation programs a prototype supporting all four degrees of freedom of one finger was build (s. Figure 1). The device can be easily attached and also be adjusted to deformed and scarred hands. In view of the fact that a lot of hand injuries affect only one finger, this prototype could already be functional in physical therapy. This paper presents the construction and the control system of the hand exoskeleton and possible applications in therapy of hand injuries. For the position control a PID controller was implemented and evaluated. The resulting control system allows following of recorded trajectories with sufficient accuracy.**

Index Terms – hand exoskeleton, rehabilitation, human-machine interaction

I. Introduction

Hand injuries are a common result of accidents. Especially the rate of hand injuries as a result of occupational accidents is high [1]. Permanent impairments are common results from these injuries [2]. Due to the frequency of occurrence economic consequences are following [3, 4]. After hand operations it is essential to perform rehabilitation to regain previous dexterity. Social and economic consequences are severe if the result of rehabilitation is not optimal. As an example rehabilitation is necessary to treat flexor tendon injuries or to avoid scarring and adhesion after surgery. Another problem during the rehabilitation process is lack of reproducible measurements. These are needed to identify limitations in the dexterity of the hand and to evaluate the progress of rehabilitation.

Currently most rehabilitation is performed manually by physiotherapists. High personnel costs and lack of motivation of patients to perform exercises at home present a problem. Some devices support physiotherapists by applying a continuous passive motion to the patient's hand, e.g. [5]. These devices are limited in the number of independently actuated degrees of freedom, and do not integrate sensors for diagnostics. The evaluation of progress is therefore done manually by the therapist. More flexible robotic support in rehabilitation of hand injuries is not common. The proposed hand exoskeleton can improve the rehabilitation process. Robotic support in rehabilitation for other human extremities has already shown promising results [6, 7].

Research on hand exoskeletons is still going on. The result of this work concerning application of exoskeletons in medical application will be briefly presented. The majority of hand exoskeleton devices were not developed with focus on rehabilitation purposes. Therefore, hand exoskeletons developed for other applications will be considered as well. Main applications are haptic interaction with a virtual reality or remote manipulations with robot arms.

Some hand exoskeletons developed for virtual reality restrict motions of the joints and do not exert them actively. For application in virtual reality this concept is suitable but for rehabilitation purposes its use is limited because finger joints should be moved by the mechanical construction. An exoskeleton that uses ultrasonic clutches was presented in [8]. The commercially available *CyberGrasp from Immersion* restricts motion by pull cables with brakes on their distant end.

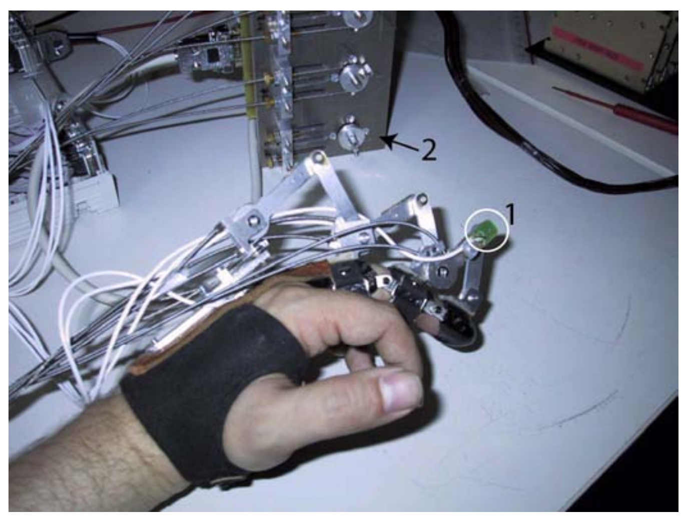

Figure 1 Prototype of the exoskeleton for one finger attached to the author's hand. Four degrees of freedom are actuated bidirectional by the use of two Bowden cables and levers for each finger joint. On each lever a hall sensor (1) is attached to measure the angle of the finger joints accurately. Actuator unit is shown in the background (2).

Other devices developed to support virtual reality applications can only exert forces in one direction. This is sufficient to allow haptic feedback for finger tips but for physical therapy a bidirectional motion is desired. An example for this type of devices was presented in [9, 10].

Many exoskeletons do not deal with all degrees of freedom of the human hand. The human finger has four degrees of freedom. Flexion and extension is possible in the metacarpophalangeal (MCP) joint, proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint. Abduction and adduction in the MCP joint is another possible motion. The PIP and DIP joint motion is coupled for the human finger. At the *Robotics Center-Ecole des Mines de Paris* a hand exoskeleton was developed that supports bidirectional movement for two fingers [11]. The system supports three degrees of freedom for the index finger and four degrees of freedom for the thumb but controls only one degree of freedom at the same time through a pull cable.

Some devices are similar to the hand exoskeleton presented in this paper. To the knowledge of the authors they were not yet used for rehabilitation purposes [12, 13]. The *LRP Hand Master* supports 14 bidirectional actuated degrees of freedom. The abduction and adduction of the fingers is supported passively.

Recent research on the usage of exoskeletons in physical therapy was done by scientists of the University of Salford [14]. They point out the necessity of robotic support in diagnostics, physical therapy, and occupational therapy. For their experiments they used a tendon driven exoskeleton which controls flexion of two degrees of freedom per finger. The *Rutgers Master II* is capable of controlling four fingers with one degree of freedom each [15]. Four pneumatic pistons inside the palm are actuating the fingers. The device was employed in a study for the rehabilitation of stroke patients. The performed exercises supported by virtual reality showed measurable success [16]. Another example for an exoskeleton used in rehabilitation showed the possibility to improve the rehabilitation progress as well [17].

Some exoskeleton devices are using ultrasonic motors which can produce high torque without the need of gear transmission [18, 19]. Although this shows that hand exoskeletons with direct actuation are possible the decision was made to build a tendon driven exoskeleton. This avoids problems with the integration and weight of an actuation that generates sufficient forces for rehabilitation purposes.

The next section describes the mechanical construction and the integrated sensors. In section three structure and realisation of the control system are addressed. First results are presented in section four. Conclusion of the current work and the possible future improvements are described in the last section.

II. Mechanical Construction of the Exoskeleton and Integrated Sensors

As shown before, existing exoskeleton devices do not satisfy all needs of rehabilitation. The developed hand exoskeleton was especially designed to fulfil following requirements:

- bidirectional movement
- support of four degrees of freedom for each finger
- palm should be free of mechanical elements to allow interaction with the environment

Furthermore the construction should be modular and lightweight, and easy to attach even to deformed or scarred hands.

The resulting system consists of four parts: the orthopaedic attachment, the mechanical leverage with integrated sensors, the actuator unit pulling the cables, and the controller unit. The developed hand exoskeleton moves fingers by a construction of levers. The levers are connected through Bowden cables to actuating motors which are controlled by the control unit. Flexible Bowden sheaths allow some movement of the hand in relation to the actuator unit. The bending radius of the sheaths should be limited because a small radius increases the friction. To avoid collisions the sheaths have to be guided.

A) Orthopaedic attachments

The connection to the hand and finger were build by an orthopaedic technician to allow a flexible ergonomic connection to the human hand and fingers. The attachments (one for each finger and one for the hand) are fixed by Velcro fasteners and can be put on and removed easily. The hand attachment is base point for the mechanical leverage for the finger motion. The finger attachments are the point of application of force and base point for the leverage of the subsequent joints. The finger attachment additionally stabilizes the finger joints by connecting phalanxes with flexible joints. These allow only anatomically correct forces from the mechanical construction to move the joints. Forces pulling or pushing the human joints in a wrong direction are absorbed by the flexible connection. For variation of hand sizes only these relatively cheap attachments have to be changed. This makes it simple to adapt the hand exoskeleton to different people. A collection of attachments in several different sizes would be sufficient for this task.

B) Mechanical Construction

Figure 2 shows a CAD drawing of the levers for one finger. On one side it is connected to the hand attachment and on the other side it is connected to each phalanx of the finger attachment. To adjust for small variations in hand size the base point of the leverage can be adjusted through an adjustment screw. The leverage of the exoskeleton supports independent flexion and extension in the MCP, PIP, and DIP joints. Abduction and adduction in MCP joint is supported as

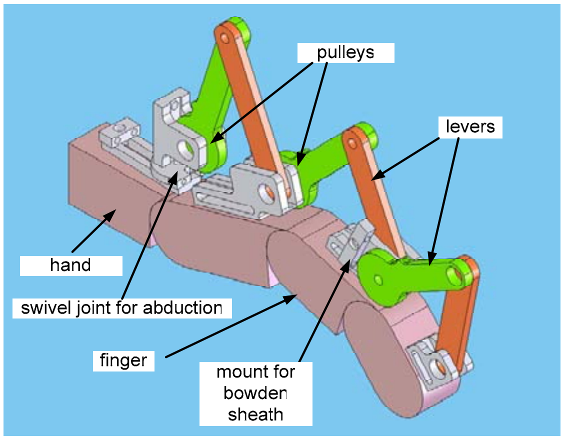

Figure 2 CAD drawing of the exoskeleton for one finger attached to a symbolized finger. Each pulley is actuated by two Bowden cables to allow bidrectional movement.

well. Exertion of force is possible in both directions. Each lever ends in a pulley where two ends of a Bowden cable are fixed. The Bowden sheaths are attached to a mount at the phalanxes. Movement of cable within the sheaths lead to a rotation of the pulleys which results in a rotation of finger joints. Each phalanx uses the preceding phalanx as base point for its motion. As a result of this, force applied to a later joint always exerts a force on the preceding point as well. All joints of the mechanical construction are supported by ball or friction bearings.

Link lengths were designed to allow nearly full flexion and extension in all joints. The allowed range of motion is shown in table 1. The link lengths were also designed to optimize directions of the applied forces. Perpendicular forces are desired but not possible to realize for all joint angles. The orthopaedic attachments compensate for this by guiding the movements. The construction was designed to be slender so that neighbouring leverages for different fingers do not interfere.

Table 1: Supported range of motion for the finger joints. For the flat hand all angles are zero. Negative angles correspond to extension resp. adduction.

Finger joint	minimum angle	maximum angle
MCP abduction/adduction	-20	20
MCP flexion/extension	-10	90
PIP flexion/extension	0	90
DIP flexion/extension	0	45

C) Actuator unit

The actuator unit (s. Figure 1) consists of four actuators to move four degrees of freedom. One unit is needed for each finger. The ends of the Bowden cables are attached to a pulley which is moved by a DC motor with transmission gears. Two Bowden sheaths for each joint are attached to a tension device to keep cables under tension reducing slackness.

Motors are controlled by PWM-controllers (Maxon ADS 50/5). These are used in torque control mode. By applying an analog voltage they supply the motors with a proportional current which results in a specific torque. The maximum torque of each motor gear combination is about four Nm.

D) Integrated sensor equipment

On one joint of each lever a hall sensor is integrated. The angle of a miniature magnet which is attached to each axis is measured by them. By trigonometric equations angles of corresponding finger joint can be calculated. To calculate this angle length of the levers and distances of their attachments to finger joints have to be known. Abduction and adduction movement is not yet measured by hall sensors. The positions of motor axes are measured by optical encoders. The value can also be used to calculate joint angles of the fingers. As a result of strain and slackness both values for joint angles can deviate.

Force sensing resistors (FSR) are attached on top and on bottom of each phalanx. They are used to measure applied forces. Forces that occur as a result of abduction and adduction are not measured yet. The resulting forces are inaccurate due to the nature of these sensors. Another problem is that they do not cover the whole contact area of the exoskeleton and the finger. The contact area is maximized by applying small distance pieces to assure that most of the force is passed through the force sensors. The values are accurate enough to measure dynamic changes in the applied forces. As a result of the pressure from the attachments measured forces are different from zero even if no force is exerted onto the phalanxes. These offsets are subtracted during later measurements.

The actual currents of the motors can deviate from the values set by the control system. These currents and therefore the torques at the motor axes are measured as well. Together with transmission ratio of gears and leverage they can be used to estimate the force exerted to the phalanges. The moments of inertia and friction have to be considered as a source of error.

Upon request of physicians the muscle activity can be measured simultaneously with the other data. Surface electromyography (sEMG) sensors are used to acquire these data. Not all muscles that are responsible for the hand movements are available to be measured by sEMG sensors on the forearm (e.g. Flexor Digitorum Superficialis or Extensor Digitorum). Other muscles can not be measured because they are not on the surface or very near to other muscles. These sEMG data are currently only arranged to be used for diagnostic support and medical research, but could be used for control of the hand exoskeleton as well.

III. Control System

The control system (s. Fig. 3) can be divided in three parts: a real-time controller, the host computer running the interface for the instructor, and the client interface giving visual feedback to the user. The user and the instructor interface can run on separate computer if desired. The different parts of the system are connected through network interfaces.

The real-time controller from *National Instruments* is running the real-time operation system *Pharlap* and samples all sensor data (hall sensors, quadrature encoders, motor currents, and force sensors) through data acquisition cards. All control loops are executed on this controller as well. The motors are driven through analog output channels which are connected to PWM-controllers. Calculation power, number of analog inputs, encoder inputs, and analog outputs are designed for the control of the complete hand exoskeleton with 20 axes. A control frequency for PID controllers of at least 1 KHz will be possible. The control system and interfaces were developed using *LabVIEW* from *National Instruments*.

The host computer running the interface for the instructor allows the setting of desired motion and displays all sensor data. The system allows recording of motion for all joints. The motion can be filtered and replayed later at a customised speed. The computer does not have to be at the same location as the rest of the system. The application can be run on any personal computer connected to the internet. This makes it possible for specialists to remotely assist patients during their exercises at home. The possibility of remote assistance is especially useful for patients living in remote areas where no specialists are available. Inconvenient travelling could be reduced.

For safety reasons the power supply is cut if an emergency button is pressed, the measured forces exert a previously defined maximum, if previously defined maximum or minimum positions are exceeded or if redundant sensors differ too much.

Several PID control loops run independently for each controlled joint. The controlled variable for each control loop is the measured angle at the quadrature encoders of the

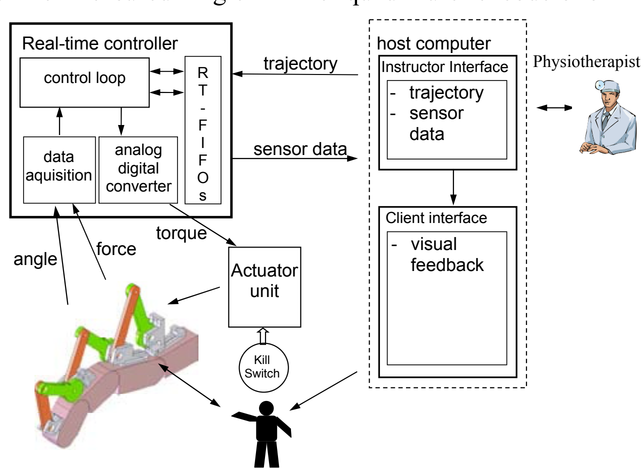

Figure 3: Diagram of the system. The Real-Time controller samples the sensors data and controls the movement through the actuation unit of the hand exoskeleton worn by the patient. The physiotherapist can supervise the exercises through the instructor interface. The kill switch can abort the movement at any time.

motors. The PID parameters of the control loops were tuned for a stable motion. Less precision in the position control is better than undesired overshoots or oscillations. The control loop currently runs at 100 Hz.

The measured angles from the hall sensors are not used inside the control loop yet. Due to the mechanical inaccuracy caused by the Bowden cables these values showed discontinuous responses. Motion of the motor axis does not necessary yield a motion of the corresponding finger joint. The consequence of this fact is an unwanted vibration if a simple PID control loop is used. The redundant angle sensors are currently only used to detect mechanical failures.

IV. Experimental Results

To evaluate the system, first experiments were performed on healthy subjects with position control. For safety reasons the motors were limited to 20% of their maximum torque so that the human wearing the exoskeleton is stronger. The performance of the PID controller was evaluated on a step response from 0 to 90 degrees for flexion of the MCP joint. The user was passive and not working with or against the motion. Figure 4 shows the recorded data for the PID controller. The performance is satisfying and deviation lies within one degree after reaching the desired value. The discontinuities while approaching the desired value are results from varying load and friction within the Bowden cables. These non-linear influences make the tuning of the system complicated and prevent tuning the PID controller to a faster response while maintaining the stability.

In the next experiment a trajectory which was recorded with deactivated actuators was used as predefined trajectory for the position control loops. The user was again passive and not working with or against the motion. Figure 5 shows the results of this experiment. The first row displays the desired trajectory and the measured values for three of the four degrees of freedom of one finger. The second row displays the applied motor torques.

In contrast to the previously presented measurement a second experiment was carried out where the user was working against the applied forces. Figure 6 shows the position and the applied torque for the MCP flexion. The difference in the resulting position accuracy is not large until the specified

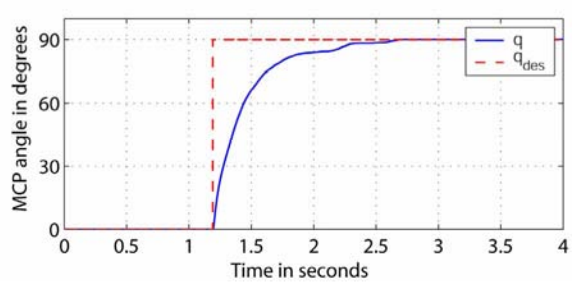

Figure 4 Step response for the flexion of the MCP joint using the PID controller. Discontinuities are result from varying load and friction within the Bowden cables.

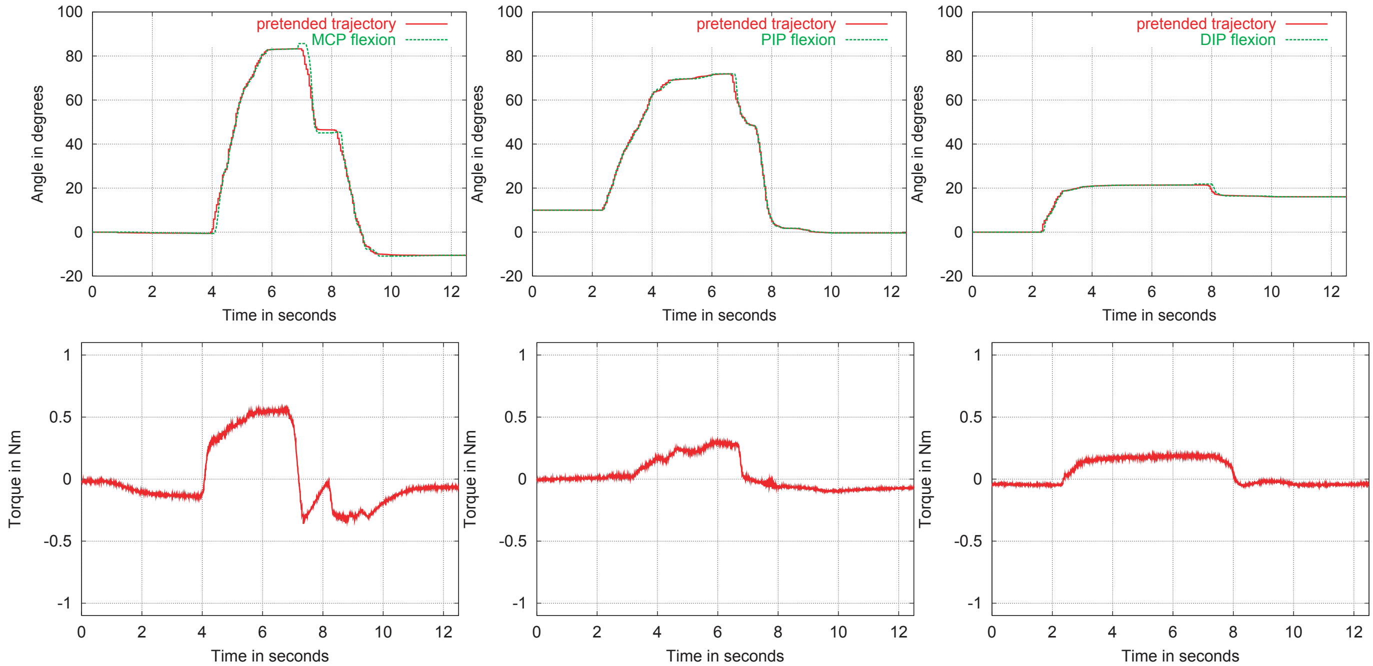

Figure 5: First row displays a comparison between desired trajectory and measured trajectory for three of the four finger joints at the first experiment where the human acts nearly passive (from left to right: flexion resp. extension for MCP, PIP, and DIP). Second row displays the torque measured at the motor taking transmission ratio of gears and leverage into account.

torque limit is reached. As suspected the position errors grow after the limit is reached. But as soon as the user reduces his resistance, position errors decrease because the torque is sufficient again. The values of the measured torque shows clearly differences to the previous experiment. These values could be used together with the data from the FSR sensors for diagnosis or for evaluation of the rehabilitation progress.

The position accuracy could be further improved by integrating the measured angles from the hall sensors. Probably the greatest source of errors is the finger attachment itself. Particularly when a lot of load is put on the phalanxes, angles of mechanical construction and finger can differ considerably. This problem can hardly be averted because of the flexibility of the skin against the bones of the finger.

V. Conclusions and Future Work

The presented work is a basis for future research and clinical studies. The hand exoskeleton was developed under consideration of the special needs of the rehabilitation. Nearly every possible trajectory of motion can be applied with sufficient accuracy. The integrated sensors allow measurements for new methods in rehabilitation and diagnostic of hand injuries. Automatic adaptation to the progress of the rehabilitation for individual patients becomes possible (e.g. by measuring their resistance to the applied motion).

Next steps will include the assembly of the hand exoskeleton to support all four fingers and the thumb. The system is already prepared for this extension. Calibrated force sensors

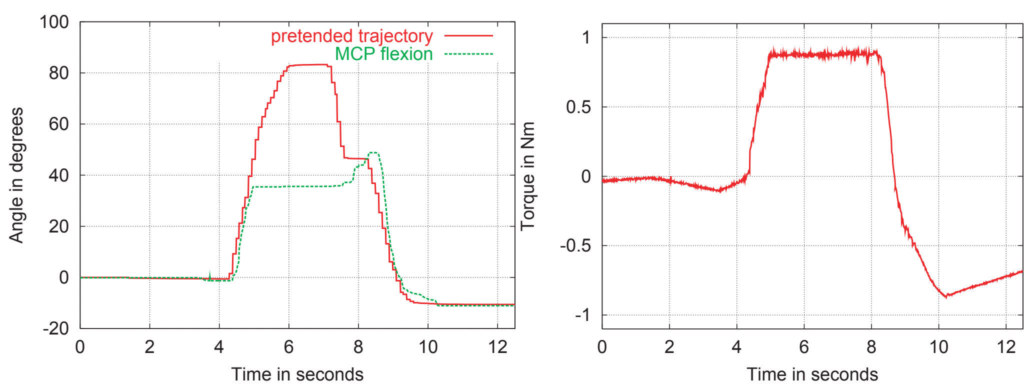

Figure 6 Same movements as in Figure 6 were performed, but the user was working hard against the imposed motion. First graphs display the trajectory of the MCP flexion. The second graph shows the applied torque. The position control can follow the trajectory until the specified torque limit is reached. After the applied force is reduced the controller can follow the predefined trajectory again. Only small overshooting can be observed.

will allow a better force measurement. The integration of an automatic calibration of the finger joint angles could simplify the usage of the exoskeleton as well [20].

Currently further experiments are on the way to improve the accuracy and stability of the position control. A modified sliding mode controller [21] was used. Prelimary experiments with this controller show promising results [22, 23]. This type of controller will probably replace the currently used PID controller. The position accuracy of the control loop could be further improved by integrating the measured angles from the hall sensors. By that measure the tolerance introduced by the flexibility of the Bowden cables could be reduced.

Further control modes incorporating the measured force will allow more flexible training programs. As an example the speed of the trajectory could be varied according to the resistance of the patient against the movement which is measured by the force sensors. This would allow the system to synchronize with the patient and avoid forcing the timing of the exercises onto the patient. The comfort of the rehabilitation program and possibly the success could be improved by this way.

Another desired control mode is a force control mode where the user is solely defining the motion by his or her movements; friction introduced by the exoskeleton will be suppressed. In this mode measurements are possible without interference of the hand exoskeleton with the patient's movements. Occupational therapy with integration of virtual reality could improve the results of the therapy as well. The inclusion of the EMG sensor data could be used to improve the quality of control by estimating the muscle forces [24]. This could be especially useful for the more ambitious control modes.

ACKNOWLEDGEMENT

The research presented in this paper was supported by the German national science foundation (DFG). The hand exoskeleton was developed in cooperation with the department for hand surgery at the university clinic of Ulm.

REFERENCES

[1] Hauptverband der gewerblichen Berufsgenossenschaften: „BGZ-Report 2/99 Arbeitsunfallstatistik“ (1999)

[2] Peters, KM; Diepenbruck, E; Frank, A.; Ingianni, G.: „Funktionelle und sozioökonomische Ergebnisse nach stationärer Rehabilitation komplex handverletzter Patienten“, Z. Orthop. Ihre Grenzgeb. 137: 516-520 (1999)

[3] Smith, ME; Auchincloss, JM; Ali, MS; "Causes and consequences of hand injury", J. Hand Surg. [Br] 10: 288-292 (1985)

[4] Johns AM: "Time off work after hand injury", Injury 12: 417-424 (1981)

[5] JACE H440 continous passive motion device for fingers: http://www.jacesystems.com/products/hand_h440.htm

[6] S. Kousidou, N.G. Tsagarakis and D.G. Caldwell: Evaluation of a "Soft" Exoskeleton for Rehabilitation and Physiotherapy of the Upper Limb Autonomous Robots July 2003, vol. 15, no. 1, pp. 21-33(13)

[7] Kiguchi, K.; Tanaka, T.; Wantanabe, K.; Fukuda, T.: Exoskeleton for Human Upper-Limb Motion Support, Proceedings of the 2003 IEEE Conference on Robotics & Automation, 2003, Taiwan

[8] Koyama, T.; Yamano, I.; Takermua, K.; Maeno, T; Development of an Ultrasonic Clutch for Multi-Fingered Exoskeleton using Passive Force Feedback for Dexterous Teleoperation, Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003, Las Vegas Nevada

[9] Avizanno, C. A.; Barbagli, F.; Frisoli, A.; Bergamasco, M.: The Hand Force Feedback: Analysis and Control of a Haptic Device for the Human Hand, Proc. of IEEE SMC 2000, Intern. Conf. on Systems, Man and Cybernetics, Nashville (TN-USA)

[10] Avizzano, C. A.; Marcheschi, S.; Angerilli, M.; Fotana, M.; Bergamasco, M.: A Multi-Finger Haptic Interface for Visually Impeared People, Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, 2003, Millbrae, California, USA

[11] Stergiopoulos, P.; Fuchs, P. and, Laurgeau, C.: Design of a 2-Finger Hand Exoskeleton for VR Grasping Simulation, EuroHaptics 2003

[12] Ohashi, T.; Ohta, M.; Hashimoto, H.; "The sensor arm and the sensor glove II - haptic devices for vr interface", Advanced Intelligent Mechatronics, 1999. Proceedings. 1999 IEEE/ASME International Conference on, 19-23 Sept. 1999 Pages: 785 - 785

[13] Tzafestas, C.S.: Whole-Hand Kinestethic Feedback and Haptic Perception in Dextrous Virtual Manipulation, IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, Vol. 33, No. 1, 2003

[14] Sarakoglou, I.; Tsagarakis, N.G.; Caldwell, D.G.: Occupational and physical therapy Using a hand exoskeleton based exerciser, Proceedings of 2004 IEEE/RSJ International Conference on Inteligent Robots and Systems, 2004, Sendai, Japan

[15] Bouzit, M.; Burdea., G.; Popescu, G.; Boian, R.: The Rutgers Master II - New Design Force-Feedback Glove, IEEE/ASME Transactions on Mechatronics, Vol. 7., No.2, June 2002

[16] Jack D.; Boian R.; Merians A.; Tremaine M.; Burdea G.; Adamovich S.; Recce M.; Poizner, M.: Virtual Reality-Enhanced Stroke Rehabilitation In: IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 9, No. 3, September 2001

[17] Brown, P.; Jones D.; Singh S.; "The Exoskeleton Glove for Control of Paralyzed Hands"; in IEEE 1993

[18] B.H. Choi and H.R. Choi: "SKK Hand Master - Hand Exoskeleton Driven by Ultrasonic Motors", International Conference on Intelligent Robots and Systems, Japan 2000

[19] Yamada, Y.; Morizono, T.; Shimorhira, S.; Umetani, Y.; Yoshida, T.; Aoki, S.: Proposal of A SkilMate Finger for EVA Gloves, Proceedings of the 2001 IEEE International Conference on Robotics & Automation Seoul, Korea, 2001

[20] Wege, A., Kondak, K., Hommel, G.: "Self-Calibrating Joint Angle Measurements for Human Fingers Using Accelerometer and Gyroscope Sensors." Proc. Mechatronics & Robotics´04, 13.09- 15.09.2004, Aachen, ISBN: 3-938153-50-X, pp.195-200, Sascha Eysoldt Verlag, Aachen

[21] K. Kondak, G. Hommel, B. Stanczyk, M. Buss. "Robust Motion Control for Robotic Systems Using Sliding Mode". Proposed for IEEE/RSJ Int. Conf. on Intelligent Robots and Systems 2005 (to appear)

[22] Wege, A., Hommel, G.: "Development and Control of a Hand Exoskeleton." Internat. Workshop on Human Interactions with Machines, 15.-16.03.2005, China, (to appear)

[23] A. Wege, K. Kondak, and G. Hommel: „Mechanical Design and Motion Control of a Hand Exoskeleton for Rehabilitation", ICMA 2005, Niagra Falls (to appear)

[24] Fleischer, Ch.,Kondak, K., Reinicke, Ch., Hommel, G.: *Online Calibration of the EMG to Force Relationship.* Proc. IROS 2004, IEEE Robotics and Automation Society, 28.9.-2.10.04, Sendai, Japan, ISBN: 0-7803-8464-4, pp. 1305-1310