10. Workshop
Automatisierungstechnische
Verfahren für die Medizin vom
29. bis 30. März 2012 in Aachen

„Novel Recording and Control Strategies for Robotic Therapy“

Urs Keller, Marco Guidali, Robert Riener
Sensory-Motor Systems Lab, Institute of Robotics and Intelligent Systems, Department of Mechanical and Process Engineering, ETH, Zurich, Switzerland
E-Mail: urs.keller@mavt.ethz.ch

Spinal Cord Injury Center, University Hospital Balgrist, Faculty of Medicine University of Zurich, Switzerland

Lucas Conditt
Healthcare and Rehabilitation Technology, Department of Biomedical Engineering, University of Applied Sciences, Technikum, Vienna, Austria

Copyright:	VDI Verlag GmbH
Band:	Fortschritt-Bericht VDI Reihe 17 Nr. 286 „Automatisierungstechnische Verfahren für die Medizin“
Editors:	Prof. Dr.-Ing. Dr. med. Steffen Leonhardt, Prof. Dr.-Ing. Dirk Abel, Prof. Dr.-Ing. Klaus Radermacher, Christian Brendle, Henry Arenbeck, Kurt Gerlach-Hahn, Kirsa Dannenberg
ISBN:	978-3-18-328617-1
Pages:	56-57

Novel Recording and Control Strategies for Robotic Therapy

Urs Keller[1,2], Marco Guidali[1,2], Lucas Conditt[3], and Robert Riener[1,2]

[1] Sensory-Motor Systems (SMS) Lab, Institute of Robotics and Intelligent Systems, Department of Mechanical and Process Engineering, ETH, Zurich, Switzerland
[2] Spinal Cord Injury Center, University Hospital Balgrist, Faculty of Medicine University of Zurich, Switzerland
[3] Healthcare and Rehabilitation Technology, Department of Biomedical Engineering, University of Applied Sciences, Technikum, Vienna, Austria

Contact: urs.keller@mavt.ethz.ch

Introduction

In the last seven years, different consecutive generations of the arm rehabilitation robot ARMin were developed at the Sensory-Motor Systems (SMS) Lab in Zurich. The last version, ARMin III, is an actuated exoskeletal structure with seven degrees of freedom (DoF) and is being used for therapy with stroke patients in four different clinics in Switzerland [1]. This year, ARMin III was transferred to the industry, with Hocoma AG (CH) building a commercial version of the device, which will be available in 2012, under the name (Armeo®Power). In parallel a new generation, ARMin IV (Fig. 1), was developed at the SMS Lab and optimized for the use with spinal cord injured (SCI) patients. A leveling caster system was attached to the base frame of the robot to adjusts its position to the patient (especially for patients with electronic wheelchair) and the software was extended. New assessments were implemented to measure patient's range of motion, movement smoothness, joint stiffness, isometric force, reaction time, etc. and the training of the tenodesis function of the hand (passive finger flexion in response to wrist extension) was enabled, which is common in tetraplegic SCI patients. Furthermore, new force/torque (F/T) sensors were mounted to improve the measurement accuracy of direct interaction between robot and patient, and thus, allow also the inclusion of rather weak patients. In the following, the focus will be laid on these sensors and particularly the associated models and force control algorithms which increase the sensitivity of the device and therefore improve the transparency.

Figure 1: ARMin IV - Arm rehabilitation robot optimized for the use with SCI patients

Methods and Materials

Measuring interaction

In order to measure interaction forces and torques in the ARMin IV, 6-DoF F/T sensors (Mini45, ATI Industrial Automation) were added in the cuffs of the upper arm and forearm, as well as in the hand module for precise measurements of patient interaction (Fig. 2).

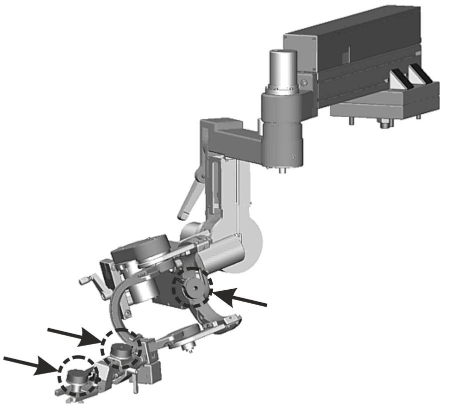

Figure 2: Positions of the F/T sensors on the exoskeleton (cuffs and hand module are invisible)

Control

The new F/T sensors can be used to directly measure the patient interaction in the cuffs of the robot. This has the advantage that even small forces, which are below the static friction of the gears and joints, can be detected. To be able to use these force/torque measurements for the joint-level torque control, the sensor information is mapped to the joints that are actuated in the robot.

This mapping is achieved by calculating the Jacobian $\mathbf{J}$, which is the position-dependant relation between the externally applied forces $\boldsymbol{f}_{S\,i}$ and torques $\boldsymbol{\tau}_{S\,i}$ on the sensor and the joint torques $\boldsymbol{\tau}_{joints}$.

$$\boldsymbol{\tau}_{joints} = \sum_{i=1}^{3} \left(\mathbf{J}^T_{f_{Si}} \boldsymbol{f}_{S\,i} + \mathbf{J}^T_{\tau_{Si}} \boldsymbol{\tau}_{S\,i} \right)$$

These six Jacobians ($\mathbf{J}_{f_{Si}}^T$,$\mathbf{J}_{\tau_{Si}}^T$, $i = \{1, 2, 3\}$) can be merged to one large Jacobian $\mathbf{J}_{tot}$, which is then multiplied by a vector $\boldsymbol{f}_{tot}$ which consists of all the force and torque components received from the three sensors:

$$\boldsymbol{\tau}_{joints}^{6\text{x}1} = \mathbf{J}_{tot}^{T\,6\text{x}18} \cdot \boldsymbol{f}_{tot}^{18\text{x}1}$$

For the control loop, the data from the sensors is first filtered with a 2nd-order 8 Hz butterworth low-pass filter before being processed through the previously calculated Jacobian, together with the robot angles $\boldsymbol{q}_{act}$. The resulting joint torques $\boldsymbol{\tau}_{joints}$ are then used in a closed-loop force controller (Fig. 3) with underlying current control.

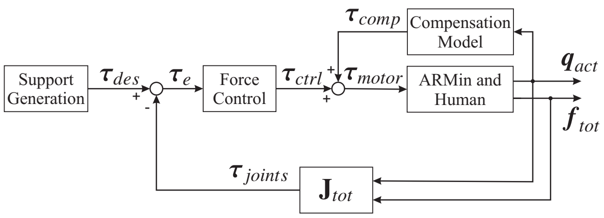

Figure 3: Force control scheme for ARMin IV

The 'Compensation Model'-block acts as a feedforward component and includes a model for the mechanical effects in the exoskeleton, i.e. the influence of friction $\boldsymbol{\tau}_f$, gravity $\boldsymbol{\tau}_g$ and springs $\boldsymbol{\tau}_s$ on the robot ($\boldsymbol{\tau}_{comp} = \boldsymbol{\tau}_f + \boldsymbol{\tau}_g + \boldsymbol{\tau}_s$) [2]. These compensation torques and the control torques are then applied to the motors of ARMin ($\boldsymbol{\tau}_{motor}$). For the following test of the force controller, a PI- and a P-controller were used. Both of them were designed by using the Ziegler-Nichols method [3]. To test the performance of the force controller the scheme (Fig. 3) was reduced to a zero-force controller by setting the reference force to zero ($\boldsymbol{\tau}_{des} = \mathbf{0}$). This provides a condition where the interaction forces/torques are maximally reduced by the controller. To have a test reference, this zero-force control condition was compared to the former compensation model.

Results

In a first single case study, a healthy subject was fixed in the ARMin and then asked to follow, joint by joint, a minimal jerk reference trajectory displayed on the screen. As an example the trajectories for elbow flexion/extension and shoulder internal/external rotation are shown (Fig. 4, left). The movement was performed for all joints (without hand opening) in three different randomized conditions with either the compensation mode, the PI-controller or the P-controller. The calculated interaction torques during the movements are exemplarily displayed for the elbow and shoulder rotation (Fig. 4, right).

To compare the different conditions the integral over the torque course was calculated. This comparison showed a reduction of interaction torques of 58% for the elbow flexion/extension (61% for shoulder internal/external rotation) for the PI-controller and 78% for the P-controller (77% for shoulder internal/external rotation) compared to the compensation model.

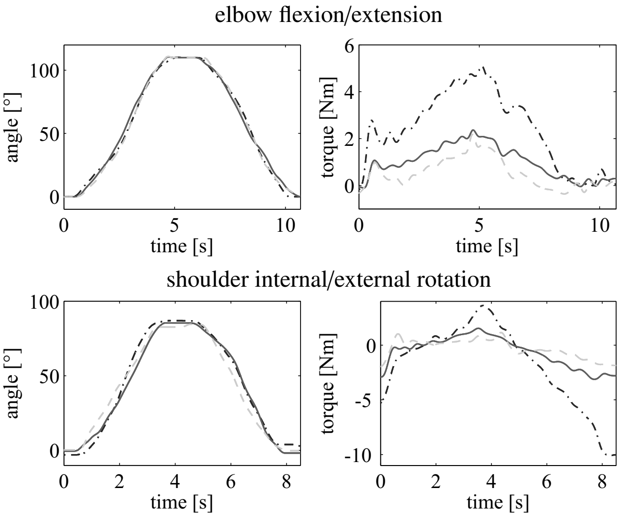

Figure 4: Angle trajectory and corresponding interaction torques for the elbow and shoulder. Dash-dotted: Compensation, solid: PI-controller, dashed: P-controller

Discussion

The results show that the F/T sensors mounted in the cuffs improve the transparency of ARMin IV by decreasing the interaction torques and forces. This is exemplarily shown for the elbow joint and the shoulder internal/external rotation. The P-controller and the PI-controller show distinct decrease of interaction torques. Whereas the PI-controller's performance is slightly worse than the P-controller. This may be due to smaller P-gains in the PI-controller compared to the P-controller. Nevertheless, it is assumed that the I-part of the controller could be beneficial for very slow movements. This will have to be tested in future.

Conclusion

The new force controller detects very small interaction forces/torques between the patient and the robot. The first version of the force controller will be integrated in the current ARMin IV software and the newly developed assessments and allows to include weak patients in the ARMin IV therapy. Furthermore, this improved transparency could be beneficial for impaired children with even smaller and weaker arms and therefore the application of the sensors in a planned pediatric ARMin is currently being investigated.

References

[1] Nef, T. ; Guidali, M. ; Riener, R.: ARMin III – arm therapy exoskeleton with an ergonomic shoulder actuation. In: *Applied Bionics and Biomechanics* 6 (2009), Nr. 2, S. 127–142

[2] Guidali, M. ; Duschau-Wicke, A. ; Broggi, S. ; Klamroth-Marganska, V. ; Nef, T. ; Riener, R.: A robotic system to train activities of daily living in a virtual environment. In: *Med and Biol Eng and Comp* (2011), S. 1–11

[3] Ziegler, J. G. ; Nichols, N. B.: Optimum settings for automatic controllers. In: *Transactions of the A. S. M. E.* 5 (1942), Nr. 11, S. 759–768