Cooperation of Passive Springs and Actuators for Energy-Efficient Exoskeletons of Upper Limb

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EXTENDED ABSTRACT

1 Introduction

The paper deals with the exoskeleton of upper limb and its energy efficient control. The current research and effort in an improvement of exoskeletons can be partly divided by muscle targeting into two main areas as lower and upper limb exoskeletons. The review [1] shows some possible approaches which deal with the design, actuation and control of exoskeletons. Special application of exoskeletons could be aimed e.g. to walking alone [2] with respect to joint design. Generally, the upper limb kinematics is much more complicated and brings topic like shoulder exoskeleton with a double parallelogram linkage as a design of the shoulder joint [3]. Exoskeletons can be divided also into two groups: wearable exoskeletons (passive, or active/semi-active) and stationary design concepts. Very interesting concept of stationary exoskeleton with redundant cable actuation is CAREX-7 (seven degrees of freedom) [4], where topics like self-identification are investigated as well. A representative of wearable exoskeleton is mentioned in [5], where the actuation is semi-active.

2 Problem Statement

The main effort of this paper is implementation of energy efficient actuation into a wearable elbow exoskeleton, which tries to take into account the natural motion of the arm during repetitive rehabilitation movements with the aim of minimizing actuation energy. The concept is based on the passive springs which can be actively tuned or adjusted during motion or adjusted for given rehabilitation movement. The idea of actuation is based on the computed torque control (CTC). The similar concept is described in [6]. The key idea is in following the natural motion of the mechanism and use actuators only to overcome the passive resistances. The paper considers similar approach which is based on "semi-active" springs to ensure the motion and its adjustment and an active actuation in parallel to also overcome the passive resistances and to fully satisfy the motion requests of rehabilitation.

3 Energy efficient motion of Exoskeleton

The considered concept of exoskeleton of upper limb consists of two joints and two semi-active springs. The possible demonstrator realization of this setup is shown in Fig. 1. The model of exoskeleton is based on two arms with two joints in planar serial configuration. The EC motors are considered as joint actuators, the arm is based on the carbon rods and the semi-active springs in both joints are considered as torsional springs. The dynamic model can be written in the form

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{f}_d = \mathbf{f}_c, \tag{1}$$

where $\mathbf{q}$ are the generalized coordinates, $\mathbf{M}$ is the mass matrix, $\mathbf{f}_d$ is a vector of disturbances, $\mathbf{N}$ is a vector of nonlinear terms, $\mathbf{f}_c$ is a vector of active forces. Subsequently, the tracking error is introduced as $\mathbf{e} = \mathbf{q}_d - \mathbf{q}$, where the vector $\mathbf{q}_d$ indicates the desired position of bodies of considered exoskeleton. Differentiating the tracking error twice and substituting from equation (1) gives $\ddot{\mathbf{e}} = \ddot{\mathbf{q}}_d - \mathbf{M}^{-1}\left(-\mathbf{N} - \mathbf{f}_d + \mathbf{f}_c\right)$. By choosing a proportional-derivative (PD) controller and after some further effort one finally has the Brunovsky canonical form:

$$\frac{d}{dt}\begin{bmatrix}\mathbf{e}\\ \dot{\mathbf{e}}\end{bmatrix} = \begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{K}_p & -\mathbf{K}_d\end{bmatrix}\begin{bmatrix}\mathbf{e}\\ \dot{\mathbf{e}}\end{bmatrix} + \begin{bmatrix}\mathbf{0}\\ \mathbf{I}\end{bmatrix}\mathbf{M}^{-1}\mathbf{f}_d, \tag{2}$$

where $\mathbf{K}_d$ and $\mathbf{K}_p$ are diagonal matrices of derivative and proportional gains of CTC. The desired trajectories are considered as point to point repetitive trajectories with respect to the natural arm motion for the purpose of simulation and are based on rehabilitation exercises. The tuning of the regulator and the choice of the actuators is considered with respect to their maximum torque to accomplish the safety demands.

The simulation results shows that the suitable spring setup in connection with known desired trajectory leads to significant reduction of the actuator force, where the passive spring ideally ensures the whole motion demand.

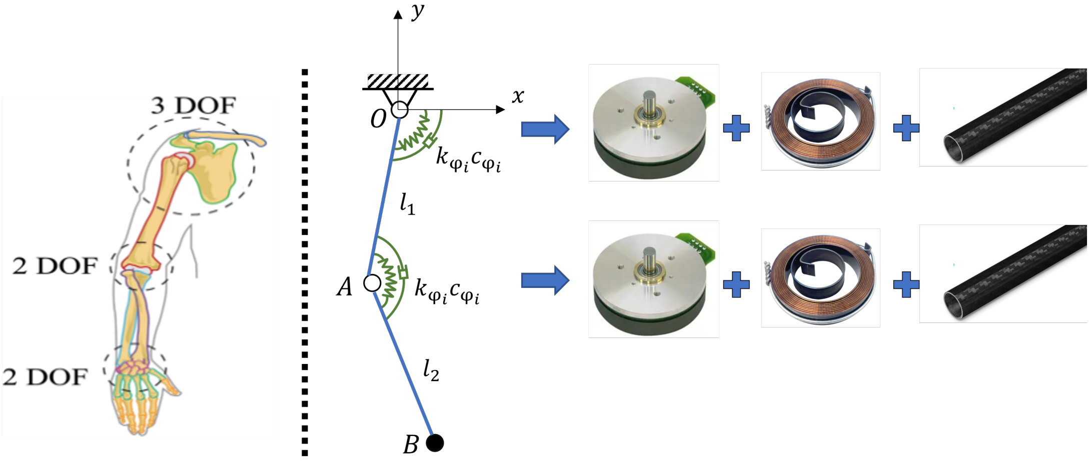

Figure 1: Kinematic description of upper limb of the left and its concept of possible realization of demonstrator of wearable exoskeleton with passive torsional springs, flat based EC motors and carbon rods on the right.

4 Conclusion

The concept of energy efficient control of exoskeleton of upper limb is discussed and proposed. The exoskeleton consists of semi-passive elements, which are represented by springs with active adjustment and actuators. The control strategy is based on computed torque control strategy. The setup of passive spring and its adjustment are considered with respect to the natural motion of the arm. The simulation results show that with proper springs setup the actuation demands could be significantly reduced. The authors plan the implementation of this approach also experimentally. The authors also suppose that the trajectory generation will be given more precisely in future by an external measuring of the natural arm motion.

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References

[1] J. A. de la Tejera, R. Bustamante-Bello, R. Ramirez-Mendoza and J. Izquierdo-Reyes, “Systematic Review of Exoskeletons towards a General Categorization Model Proposal,” Applied Sciences, vol. 11, no. 1, p. 76, 24 December 2020.

[2] M. Shourijeh and B. Fregly, “Muscle Synergies Modify Optimization Estimates of Joint Stiffness During Walking,” Journal of Biomechanical Engineering, vol. 142, no. 011011, 1 October 2019.

[3] S. Christensen and S. Bai, “Kinematic analysis and design of a novel shoulder exoskeleton using a double parallelogram linkage,” Journal of Mechanisms and Robotics, vol. 10, no. 4, p. 041008 (10 pages), 1 August 2018.

[4] X. Cui, W. Chen, X. Jin and S. K. Agrawal, “ Design of a 7-DOF cable-driven arm exoskeleton (CAREX-7) and a controller for dexterous motion training or assistance,” IEEE/ASME Transactions on Mechatronics, vol. 22, no. 1, pp. 161-172, 2016.

[5] A. Zahedi, Y. Wang, U. Martinez-Hernandez and D. Zhang, “A wearable elbow exoskeleton for tremor suppression equipped with rotational semi-active actuator,” Mechanical Systems and Signal Processing, vol. 157, p. 107674, 2021.

[6] KRIVOŠEJ, J. and Z. ŠIKA. Eigenmotion Concept of Cable Driven Mechanism with Absorbing Elements. In: PROCEEDINGS OF COMPUTATIONAL MECHANICS 2022. Computational Mechanics 2022, Srní, 2022-11-07/2022-11-09. Plzeň: University of West Bohemia, 2022. p. 59-60. ISBN 978-80-261-1116-0. Available from: http://dspace5.zcu.cz