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Preliminary test of a zero-torque controlled exoskeleton on a treadmill

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Abstract: Variable stiffness actuators help to guarantee a safe human interaction when it is used as the active joints in lower-limb exoskeletons. Therefore, we designed a unilateral exoskeleton consisting of a mechanical-rotary variable impedance actuator (MeRIA) assisting the human knee. In this paper, a first walking trial with a healthy, human subject has been carried out on a treadmill to validate the mechanical performance of the actuator. Even though the implemented zero-torque controller does not yet actively strengthen the human subject, the preliminary test shows that the exoskeleton can follow the human motion while providing a low impedance and thus a patient-cooperative behavior during walking.

I. Introduction

A wearable lower-limb exoskeleton can be designed to assist the human gait by providing additional torques at the subject's joints using electric or other energy-based actuators, which can be applied for supporting age-related diseases and partial gait disorders, e.g., post-stroke hemiplegic patients [1-2]. Therefore, it is crucial to achieving a safe interaction between a human and the machine. Variable impedance actuators address this challenge, and they are often used in applications with a physical interaction between human subjects and robots [3-6].

We proposed in [5] a tailored-made compliant actuator, composing of a mechanical-rotary variable impedance actuator (MeRIA). The main idea behind this actuator is to transfer the generated motor torque via an adaptable elasticity to the human joint. The series elasticity is realized by two leaf springs and allows smooth interaction between the stiff motor and the compliant knee joint of the patient.

Our goal is to achieve a patient-cooperative control for an active knee orthosis consisting of the MeRIA that follows the subject during walking. The implemented control strategy is presented in [6] and consists of a zero-torque control extended by a disturbance observer, rendering the human-machine interaction.

In this paper, we present a first walking trial on a treadmill with a healthy, human subject. The purpose of this preliminary test is not only to evaluate the performance of the MeRIA at the joint level but also to simulate a patient-cooperative control by varying the stiffness during walking.

II. Material and methods

The prototype of the unilateral, lower-limb exoskeleton considered in this paper has one active knee joint, which consists of the MeRIA, as shown in Fig. 1. This actuator includes two motors. The first motor (M1) generates the main torque for assisting the patient that is transferred via a Harmonic Drive and two leaf springs to the output shaft. The effective length of the two leaf springs, hence, the stiffness of the actuator, can be changed during operation by moving two cam followers along the springs using the second motor (M2). The output shaft is attached to the subject's knee joint using belts at the thigh and the lower leg of the human.

The difference between the torque that is generated by the actuator (M1) at the output shaft τ_j and the joint torque due to the dynamics of the mechanism τ_l is called the interaction torque:

$$\tau_{int} = \tau_l - \tau_j. \quad (1)$$

By measuring the deformation of the leaf springs with strain gauges (see Fig. 1), the actuator torque can be determined. In addition, the angular position of the knee is measured using a 14-bit encoder (Orbis, PWM interface, Renishaw GmbH, Pliezhausen, Germany).

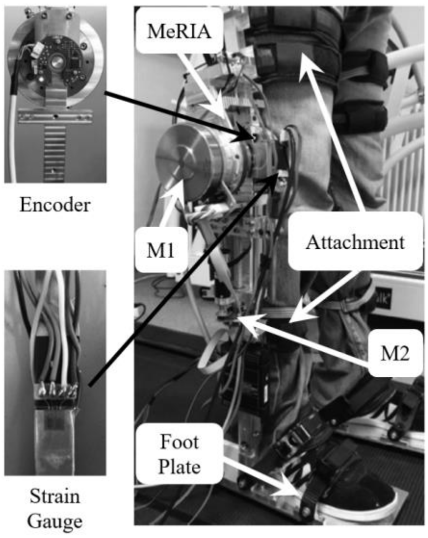

Figure 1: Setup of the unilateral lower limb exoskeleton with the MeRIA on a treatmill.

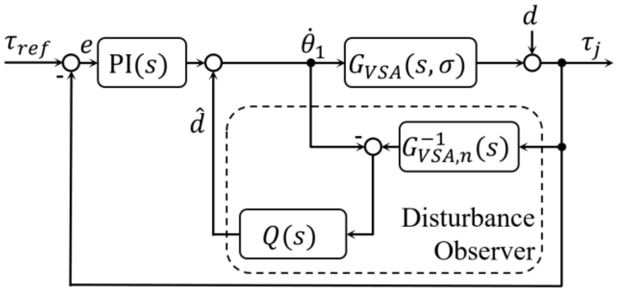

Figure 2: Zero-torque controller realized with a PI feedback controller extended by a disturbance observer for estimating the input disturbance d as proposed in [6].

For the control of the MeRIA, a PI torque controller with an additional Disturbance Observer (DO) is implemented as proposed in [6] (see Fig. 2).

In Figure 2, $G_{VSA}(s,\sigma)$ denotes the linear transfer function of M1 from a reference input angular velocity $\dot{\theta}_1$ to the output torque τ_j which is dependent on the online changeable stiffness $\sigma \in (\underline{\sigma}, \bar{\sigma}) = \left(201 \frac{\text{Nm}}{\text{rad}}, 455 \frac{\text{Nm}}{\text{rad}}\right)$. The disturbance observer estimates the input disturbance (indirectly describes the human movement) and is realized by taking the inverse of a nominal model

$$G_{VSA,n}(s) = G_{VSA}\left(s, 350 \frac{\text{Nm}}{\text{rad}}\right). \quad (2)$$

The nominal model $G_{VSA,n}$ is extended by a low pass filter $Q(s)$ with a cut-off frequency of 0.5 Hz.

The goal of the preliminary walking test is that the exoskeleton follows the subject's movement during the treatmill walk. For that, the reference torque τ_{ref} of the controller was set to zero. The stiffness was adjusted depending on the human torque that is estimated by the DO to achieve a low impedance when needed. The stiffness was set to a high level if no disturbance occurred. A high value was set in case of an estimated disturbance.

During the walking experiment, the subject was asked to walk slowly with the exoskeleton on a treadmill. For safety reasons, the subject was attached to a suspension system. The zero-torque controller and the stiffness adjustment were computed in real-time on a dSpace DS1103 System (dSpace, Paderborn, Germany).

III. Results and discussion

Figure 3 shows the measured joint torque τ_j over four steps. Each step consists of a stance phase and a swing phase of the assisted leg. In the torque measurement shown in Fig. 3, the stance phase is indicated by the parts of the curve in which the interaction torque is around zero. During this phase, the stiffness is kept at the maximum value. When the assisted leg of the patient changes from the stance phase to the swing phase, the disturbance can be measured, and thus this simulates the increased interaction torque between the human and the exoskeleton. This interaction is observed by the DO as a disturbance. Accordingly, the stiffness is varied from high to low to achieve a low-impedance. Simultaneously, the exoskeleton follows the human motion due to the implemented zero-torque control.

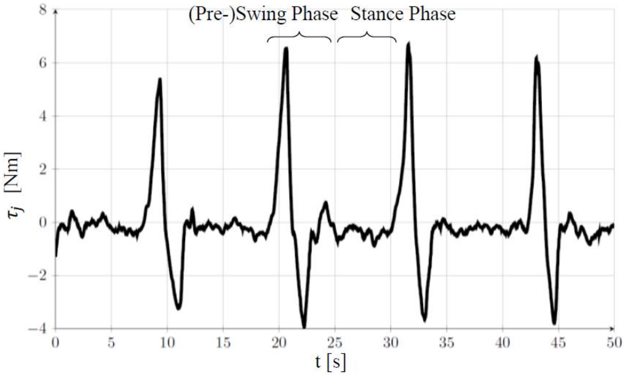

Figure 3: Measured joint torque τ_j between the human and exoskeleton during four gait cycles on a treadmill.

Note that to walk, the subject must induce a torque into the exoskeleton. This means that the exoskeleton does not yet actively support the test person. However, during the treadmill test the MeRIA was able to follow human movement without exceeding a joint torque of 7 Nm. Simultaniously, the MeRIA was able to ensure a variable stiffness. Thus, the potential to develop a patient-cooperative control framework based on the VSA is given.

IV. Conclusions and outlook

The preliminary test has shown that the mechanical structure of the MeRIA proposed in [5] can follow the human motion during walking on a treadmill. However, the implemented zero-torque control allows the exoskeleton only to follow the human movement. Therefore, a future task is to extend the proposed control strategy to support the human motion actively and to assist hemiplegic patients during rehabilitation.

AUTHOR'S STATEMENT

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The Ethics Committee was informed about the self-experiment under file number EK 145/18.

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