Undesired Constraint Forces in non-ergonomic wearable Exoskeletons

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I. INTRODUCTION

Exoskeleton robots are currently being developed in many research lab's for the rehabilitation of patients suffering from injuries to the nervous system. A multitude of exoskeletons for interaction with the human limb are proposed for rehabilitation training, ranging from external, end-point based devices to wearable full limb exoskeletons [1]. Their ability to smoothly interact with the human subject is crucial for successful application in physical therapy. It is important that devices interacting closely with a human limb are intrinsically safe, comfortable and are able to exploit the full range of natural motion for movement training. The two main aspects that need good consideration are the implementation of the actuation and motor control, as well as the intrinsic mechanical and kinematic design of their structure.

Still a couple of years ago, such rehabilitation exoskeletons were mostly equipped with motor controllers that dictate movement to the patient. While this seemed to suffice during the childhood of such devices, now, researchers want more freedom to implement assistive therapy protocols as well. In patient assist therapies, the rehabilitation devices actuation supports, but does not impose, the natural movement of the patient during training. Sophisticated controller concepts based on impedance and admittance control are currently being implemented in such rehabilitation devices. Hybrid controllers in rehabilitation exoskeletons provide already significantly better safety for the user than the earlier position controlled devices. Thus, from an actuation and motor control point of view, safety and user comfort criteria can be satisfied.

An area, however, to which too little attention is paid, is the appropriate kinematic design of the rehabilitation device structure. If the kinematic setting of a rehabilitation robot is not well matched to the patient, undesired interaction forces can be created during motion, even if no actuation is provided at all. Those constraint forces can be large in magnitude and provide a safety hazard as well as discomfort to the user. It is interesting to note that such forces, stemming mostly from misalignments between the device's axis of motion and the human limb, can usually not be compensated by the device's actuators. Kinematic mismatches between the Lokomat leg orthosis and patient legs, for instance, were already shown to be responsible for injuries and discomfort. This was reported in [2] and [3]. Furthermore, it was shown in [4] that kinematic mismatch between an orthosis and a patient can alter the natural muscle activation patterns. This is counterproductive during physical therapy and could also lead to injury.

II. CONTENT OF PROPOSED PRESENTATION

Based on such observations, in 2006, we have developed a novel design paradigm for better mechanical and kinematic exoskeleton designs. The paradigm was presented in [5] on the example of the ESA ergonomic human arm exoskeleton.

In the work to be presented, we show a theoretical model which serves to quantify the interaction quality between a patient and an orthosis or exoskeleton. We developed an explicit analytical model of a human limb interacting dynamically with an exoskeleton of conventional structure (The exoskeleton axes are aligned with the estimated human joint centers of rotation). In reality, the exoskeleton principal axes are always slightly offset from the true position of the biological joints. In our model, we can insert those offsets and determine the expected interface forces between the biological limb and the exoskeleton during motion. We have validated predictions from the model with an experimental campaign, to which 14 real subjects of different statue participated. We will describe the detailed protocol of the experiment in the presentation. We show that large forces, up to 200 N, can be created during movement of the forearm of an operator, if kinematic mismatches in the order of a couple of cm between an elbow exoskeleton and the human elbow exist. That is without actuation! We used a part of the ESA human arm exoskeleton as an experimental device, with locked passive compensatory joints. This transformed the otherwise ergonomic device into a conventional exoskeleton that requires alignment to the human joints.

Figure 1 shows the overall exoskeleton as it was used during a training session with an ESA astronaut.

In Figure 2, the elbow articulation of the ESA exoskeleton is depicted that was used for the experimental validation of the human-robot interaction model. Forces and Torques stemming from kinematic mismatch were recorded with a 6 dof F/T Sensor during signal tracking tasks. Figure 3 shows an extract of the measured data. In Figure 3 (top), a boxplot of the measured longitudinal forces is shown over the elbow position. The data displayed is the total inter-subject data.

These boxplots allows interpreting the magnitudes of the longitudinal forces that are created along the forearm purely from kinematic mismatch. In Figure 3 (bottom), the mean values of the same data are shown. The model prediction of the constraint force is shown with a dashed line. As can be seen, over the entire range of motion, constraint forces exist. Their magnitudes are sufficiently large to provide discomfort to the operators. This is especially significant for long-duration tasks.

In our presentation we would like to explain in more detail the characteristics of this behavior, as well as propose solutions to this problem that is inherent to most exoskeleton designs.

The data evaluation of this experiment is still ongoing at this point in time, which is why we trust that the content could be very suitable for a workshop presentation on assistive technologies. We hope to be able to give these critical inputs to the community to help designing better devices, that better fit different individuals.

Figure 1: The ESA Human Arm Exoskeleton as worn by ESA astronaut Claude Nicolier during a training session with a teleoperated robot EUROBOT.

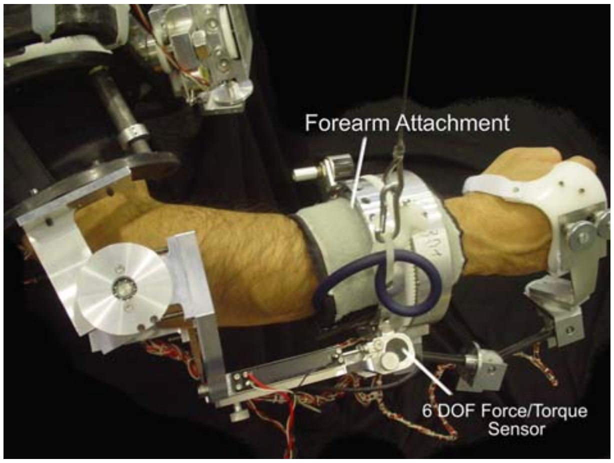

Figure 2: The elbow articulation of the EXARM exoskeleton that was used for the experimental validation of the human-robot interaction model.

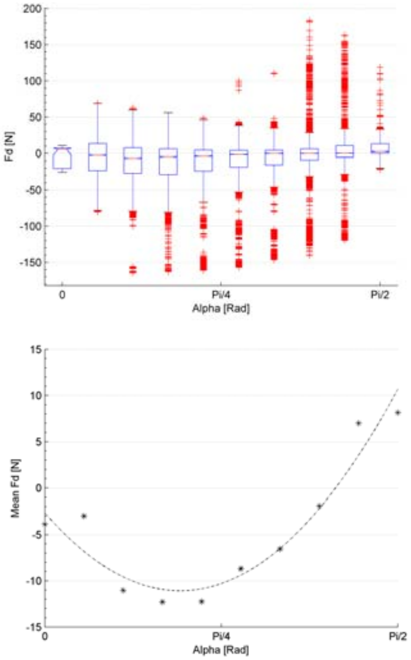

Figure 3: Top: Boxplot of longitudinal interaction force (along forearm) over the elbow position. Complete data from 14 Subjects. Bottom: Mean values of the longitudinal force over elbow position (asterisk) and model prediction (dashed line).

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