Human-Exoskeleton Interfaces Design and their Impact on Interaction

Dorian Verdel, Guillaume Sahm, Simon Bastide, Olivier Bruneau, Bastien Berret, Nicolas Vignais

I. INTRODUCTION

Active upper-limb exoskeletons are promising devices for numerous health and occupational applications. In particular, they could potentially be useful in preventing musculoskeletal disorders at work [1]. However, current exoskeletons are still generating unwanted changes in human movement. The situation in which the impacts of an exoskeleton on human movement are minimized is called transparency. This is often achieved by minimizing the interaction efforts between the human and the exoskeleton and by compensating for the dynamics of the robot [2]. This is necessary in many applications [3], although perfectly canceling interaction efforts cannot be achieved [4].

The quality of human-exoskeleton interaction, and therefore transparency, can be mainly improved by two methods, either by implementing new control laws [2] or by improving the mechanical design of the robots to make them more reversible and compliant [5]. Despite improvements in the mechanical transmission of exoskeletons, the physical interface between the human and the exoskeleton, which is a major part of this transmission, have received relatively little attention [4]. The interfaces are of major importance because improving their design is a solution to compensate for joint misalignments (JM) that inevitably appear when a human is wearing an exoskeleton [4], [6]. A first model based on planar geometry was proposed to analyze the effects of JM on the upper limb in the sagittal plane [6]. A more general approach was then introduced, based on general mechanisms theory, which allowed to design self-aligning mechanisms compensating for JM [4].

Nevertheless, the impact of such self-aligning human-exoskeleton interfaces (HEI) has not been systematically investigated in terms of human-exoskeleton interaction efforts, human movement kinematics, muscle activity, movement efficiency and individual feeling. The present study aims at analyzing the influence of different HEI on both biomechanical parameters and subjective perception. The methodology presented in Section II. The obtained results are then presented and discussed in Section III.

D. Verdel, G. Sahm, S. Bastide, N. Vignais and B. Berret were with the CIAMS, Université Paris-Saclay, 91405 Orsay, France and with the CIAMS, Université d'Orléans, Orléans, France. Corresponding e-mail: dorian.verdel@universite-paris-saclay.fr.

O. Bruneau was with the LURPA, ENS Paris-Saclay, 91190 Gif-sur-Yvette, France.

B. Berret was with the Institut Universitaire de France, Paris, France.

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II. METHODS

A. Exoskeleton and control method

The exoskeleton used in the present study is called ABLE [5]. This exoskeleton presents the major advantage of being highly reversible and compliant thanks to its mechanical design. In the present study, only the elbow axis of the exoskeleton was controlled to assess the effects of different physical interfaces on simple movements (i.e. flexion/extension of the human elbow). The transparent control is based on identification and compensation of the dynamics of the elbow joint and on an interaction force minimization, which is achieved via interaction efforts measurements with a force/torque (FT) sensor [2], [7]. The experimental setup is described in Figure 1a.

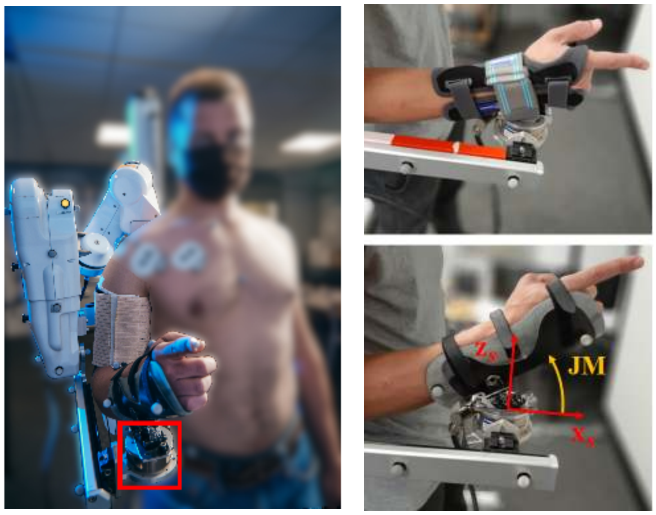
B. Tested interfaces

Three different HEI were used to assess the impact of HEI design on human movement. The first HEI was composed of a basic strap and did not include any passive mobility. A light splint was used with this HEI to prevent the participant from using their wrist during the experiment. This interface served as a baseline (it will be called BAS) corresponding to what is usually provided by exoskeleton manufacturers. The other two tested HEI were composed of the same thermoformed orthoses coupled to different passive mobility. The first of these includes a passive translation along the robot forearm segment (it will be called ORT_T). The second one included two supplementary rotations around $\mathbf{y_s} = \mathbf{z_s} \times \mathbf{x_s}$ and $\mathbf{z_s}$ (it will be called ORT_R). The different HEI and the definition of these axes are described in Figure 1b.

C. Experimentation

a) Participants: 18 healthy right-handed participants took part in the experiment (11 females and 7 males). Averaged anthropometric characteristics of the participants were the following: age 25 ± 6 years old, height 171.9 ± 7.9 cm, weight 64.8 ± 11 kg, arm length 28.6 ± 2.8 cm, forearm length 25.3 ± 1.8 cm and hand length 19.2 ± 1.3 cm. The experimental protocol was approved by the local ethical committee for research (CER-Paris-Saclay-2021-048) and the written consent of participants was obtained as required by the Helsinki declaration.

b) Task: The task consisted of 60° point-to-point reaching movements in the sagittal plane involving elbow flexion/extension movements. The targets were materialized by LEDs that lit successively 3 cm away from the tip of the index finger of the participant. First, participants performed a block of 30 pointing movements outside the exoskeleton



(a) (b)

Fig. 1: Robot and experimental set-up. (a) ABLE exoskeleton used in the present study, the FT sensor is the part in the red square. (b) Physical human-exoskeleton interfaces (top: BAS HEI, bottom: ORT_T and ORT_R HEIs, reference frame and an example of JM).

(referred to as NE for No Exoskeleton). Then they performed three blocks, one with each HEI, in a randomized order.

c) Materials and data processing: Interaction forces and torques were measured by the FT sensor (see Figure 1a), directly at the connection level. FT data were low-pass filtered (Butterworth, fifth order, 5 Hz cut-off).

Kinematics were measured by means of an optoelectronic device (Qualisys, Göteborg, Sweden). The position data hereby measured were low-pass filtered (Butterworth, fifth order, 5 Hz cut-off). Numerical differentiation was then performed to compute the velocities and accelerations.

Electromyographic activities were measured by means of four surface EMG devices (Wave Plus wireless EMG system, Cometa, Italy). The EMG signals were treated following well-known procedures [2], which allowed to obtain filtered, normalized and rectified data.

The movement efficiency was defined as the ratio between the agonist burst and peak acceleration in each condition, normalized by the value obtained in the NE condition as previously defined and rationalized [2], [7].

d) Statistical analyses: Differences between conditions were first assessed by means of repeated measurements ANOVAs. Post-hoc consisted of pairwise t-tests. All significance levels were set at ($p < 0.05$).

III. RESULTS AND DISCUSSION

a) Biomechanical parameters: The addition of passive degrees of freedom allowed to significantly reduce unwanted interaction efforts due to kinematic incompatibility. In particular the ORT_R condition allowed a reduction of all the unwanted interaction efforts measured in the BAS condition. On the contrary, the ORT_T HEI led to reduced efforts along $\mathbf{x_s}$ but highly increased the interaction torque around $\mathbf{y_s}$, due to the interaction area increase without additional mobility.

Kinematics were also significantly affected by the different HEIs. In particular, the peak acceleration and peak velocity were significantly lower than in the NE condition for both the BAS and ORT_R conditions. Although some part of these differences can be explained by the fact that the control did not completely compensate for the inertia of the exoskeleton, the HEI seems to be an important factor to minimize the impact of the exoskeleton on human kinematics.

The same trend was observed on the muscle activation and movement relative efficiency. For both of these analyses, the ORT_T condition impacted significantly worse than the BAS condition and the ORT_R condition was not statistically different from the NE condition. These results highlight the fact that increasing the interaction area, which is suggested in previous studies [4], must be concomitant with the inclusion of passive degrees of freedom.

b) Individual feeling: Participants gave significantly better grades to the ORT_R interface on all the tested parameters except accuracy (all the tested HEI were graded equivalently on this parameter). The grades given to the BAS and ORT_T conditions were not significantly different. Nevertheless, the average grades of the ORT_T condition were slightly better than those of the BAS condition.

IV. CONCLUSIONS

The present paper introduced a systematic evaluation of the impact of various HEI on both biomechanical and subjective feeling parameters. The conducted analyses allow to recommend both an increase in the interaction area and the addition of passive degrees of freedom when designing a human-exoskeleton interface. In order to minimize unwanted interaction efforts, movement perturbations and to maximize comfort, both increased interaction area and passive degrees of freedom must be introduced simultaneously.

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