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Dynamics modeling of physical Human-Robot Interaction for Lower Limb Exoskeletons design evaluation

Riccardo Bezzini, Fracesco Porcini, Carlo Alberto Avizzano, Alessandro Filippeschi
Institute of Mechanical Intelligence, Sant'Anna School of Advanced Studies, Pisa, 56127, Italy.
r.bezzini@santannapisa.it, f.porcini@santannapisa.it, c.avizzano@santannapisa.it, a.filippeschi@santannapisa.it

***Abstract*—Accurate knowledge of the physical Human-Robot Interaction (pHRI) is essential for designing efficient and comfortable exoskeletons. The abundance of complications and limits deriving from straightforwardly measuring the Human Exoskeleton (HE) interaction wrenches stress the importance of building pHRI dynamics models. This study examines, through a flexible model, the effects of different connection mechanisms (i.e., harnesses) between a Lower Limb Exoskeleton and a wearer during a gait cycle. This evaluation is based on minimizing the interaction wrenches through optimization of HE contact impedance and investigating the exoskeleton dynamics resulting from a simulated pHRI model. Multiple arrangements were explored as a preliminary validation, resulting in consistent impedances at the interfaces and simulated HE kinematics.**

***Index Terms*—Human-Exoskeleton model, physical Human-Robot Interaction, Optimization, Kinematics, Impedance**

I. Introduction and Related Work

Exoskeletons are wearable robotic systems that assist the users while following their movements. The human-exoskeleton (HE) connections should guarantee proper performance of the device by limiting the exertion of undesired interaction wrenches, i.e. the exoskeleton must be transparent.

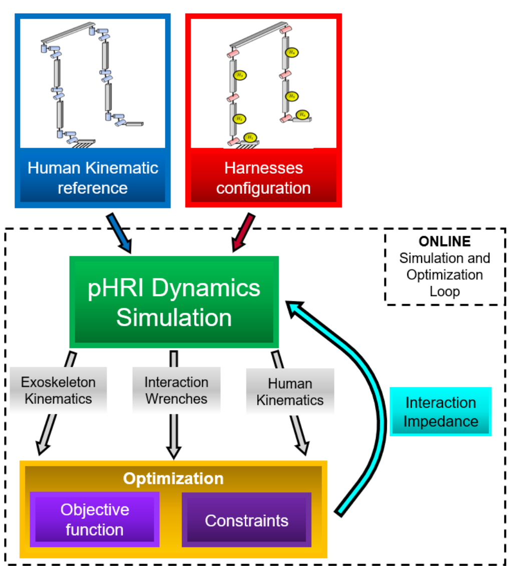

Fig. 1. Schematic overview of the proposed approach for the pHRI simulation and the interaction impedance optimization for evaluating different Human-Exoskeleton connection arrangements.

The study of unpredictable forces on the human body is a fundamental concern in pHRI. Despite the value of practical tests for assessing the exoskeleton's performances, it is clear that building a prototype, testing it, evaluating its performances, and starting over this cycle lead to a long and expensive process for the assessment of a lower limb exoskeleton (LLE). Therefore, modeling the HE dynamics emerges as a valuable approach for evaluating wearable devices. However, to the authors' knowledge, most of the current works reduce the analysis to planar or partial models and overly simple contact modelization. Furthermore, not all the conclusions inferred by examining a specific exoskeleton are necessarily generalizable to other devices, undermining the replicability and significance of the results. Serrancoli et al. [1] analyzed the sit-to-stand task using an LLE model limited to the sagittal plane. To explore the effects of different cuffs, Sun et al. [2] explore the effects of different thigh cuffs just in static settings. Guitteny et al. [3] estimated only the contact stiffness at the thigh and shank interfaces during numerous activities (squatting, level walking, etc.) Yan et al. [4] developed a planar model describing the HE swing dynamics at the thigh and shank interfaces.
Examining the reported works, which, to the author's knowledge, represent the main contributions regarding HE pHRI modeling, a few limitations are derived and stressed in relation to the features of the approach applied in this study:

- No complete 3D exoskeleton models are built.
- Only some of the HE contact points are considered.
- The impedances at the interfaces often do not include three rotational-linear stiffness-damping parameters.
- Each mentioned model can represent just a single device.

II. Proposed Approach

This study employs the model presented in [5] (in press), which considers six linear and rotational spring-damper elements at each HE interface, for evaluating the effects of different harnesses on the simulated exoskeleton motion with respect to the virtual wearer. The simulated user interacts through virtual impedances (at the pelvis, thighs, shanks, and feet) with the 3D floating-base articulated exoskeleton with 42 degrees of freedom (3 flexion-extension DoFs for each leg, and 6 DoFs for each connection mechanism). The harnesses' configuration can be set freely because the same model potentially represents all the possible connection mechanisms, whose model includes six DoFs. High stiffnesses are employed to block some of the DoFs to implement a specific harness mechanism. The wearer's kinematics during a gait cycle are recorded and used for running optimizations that explore the pHRI dynamics, according to the scheme from Figure 1. The wearer determines the exoskeleton motion through the impedances at the interfaces, which are the objects of an optimization process for minimizing the interaction wrenches. The problem is constrained so that the exoskeleton kinematics cannot deviate excessively from the user's reference so that the resulting motion can reflect the actual movements.

III. Results

Figure 2 presents the exoskeleton kinematics resulting from the simulation of different harnesses' arrangements (identified through three numbers **[x y z]** that define the DoFs implemented in the mechanisms, [5]). Figures 3 and 4 report respectively the kinematics and the impedances estimations computed for cases of study that differ for the wearer's anthropometric measures (*50-th*, and *97.5-th* percentiles), and noises added to the human references.

- **C1**: *50-th* percentile, no noise on the user reference
- **C2**: *50-th* percentile, noise on the user reference
- **C3**: *97.5-th* percentile, noise on the user reference

IV. Discussion and Conclusion

In [5], we compared experimental and simulated pHRI, demonstrating the proposed method's accurate wrenches estimations. In this work, we prove that our approach also produces exoskeleton movements coherent with those of the human reference and impedance estimations consistent with a valuable combination of impedances at the HE interfaces (indeed, the six damped springs at each interface represent the series of the human limb and the harness's cuff impedances). Future works comprehend an in-depth experimental validation through further cases of study.

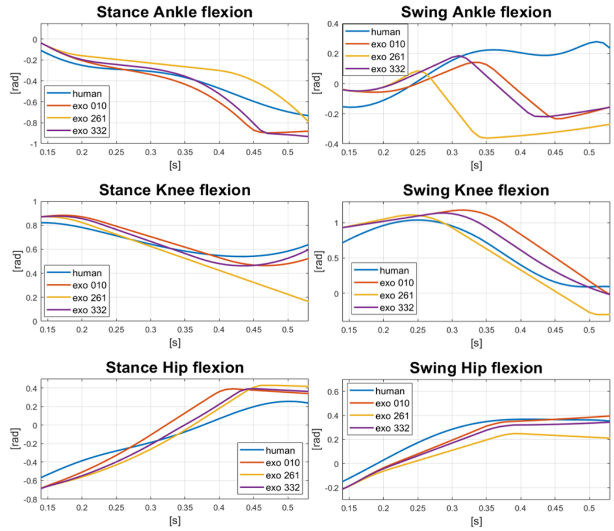

Fig. 2. Kinematics of the Ankle, Knee, and Hip joints, comparing motions resulting from simulations carried out using the same human kinematic references, but employing different harness configurations (identified through numeric codes that express the number of DoFs, see [5]).

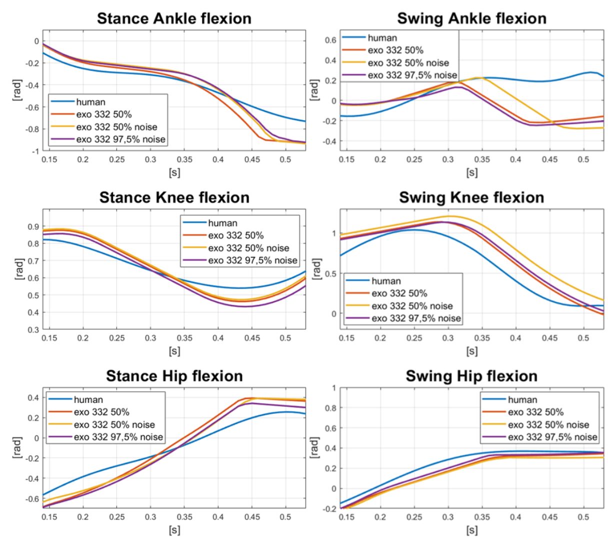

Fig. 3. Kinematics of the Ankle, Knee, and Hip joints, comparing motions resulting from simulations carried for the cases of study **C1**, **C2**, and **C3**).

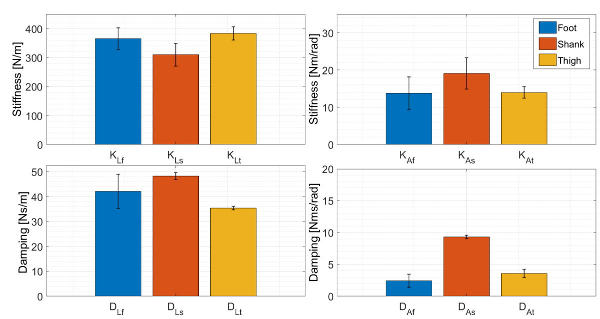

Fig. 4. Linear (L) and Angular (A) impedance parameters at the foot, shank, and thigh. The bar plots display the mean values and the standard deviations of the impedances resulting from the cases of study **C1**, **C2**, and **C3**.

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