Modeling Human-Exoskeleton Interaction: Preliminary Results

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Abstract. Physical interfaces have an important role in achieving efficient, safe and comfortable transmission of forces between the exoskeleton and the human body. They are normally composed of different compliant elements disposed in series between the skin of the user and the exoskeleton frame. Modelling how the compliant properties of physical interface will affect the transmission of forces may be useful to improve the design process towards more effective, safe and user-specific exoskeletal devices. As a first step in this direction, we propose a simplified 2-dimensional model representing the interaction of a single-actuated-joint exoskeleton with the human limb through a compliant element. We studied the effects of stiffness value associated to the tissues in the behavior of the whole system with simulated results of the model.

1 Introduction

Researchers and engineers are continuously proposing new innovative solutions to improve robotic exoskeletons that assist or rehabilitate human motion [1]. Human-centered design approaches are becoming more and more popular, due to the increasing need of solutions that can adapt to specific user's needs. Anthropometric and kinematic data is normally considered when designing and selecting the mechanical components of the exoskeletons. At the same time, adaptive control strategies are implemented to improve the human-exoskeleton symbiotic performance [2]. In this process, the physical elements that connect the human with the machine, such as cuffs and straps, are crucial for transmitting the actuation forces in an efficient, safe, and conformable manner. Appropriate quantitative method to design these components should be also considered to achieve a completely human-centered design. The effectiveness and efficiency of this transmission can be reduced by two main factors [3]: (i) the misalignments between robot and human joints, and (ii) the compliant properties of physical elements in series with human soft tissues.

In this contribution, we present a simplified model of force transmission between the exoskeleton and the human. It characterizes a simple system composed of a

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single-actuated-joint of the exoskeleton applying forces on soft tissues; connected to a static rigid-fixed human limb. We consider different stiffness values of soft tissues and observe the behavior of the system.

2 Material and Methods

2.1 Interaction model

The theoretical model shown in Fig. 1 is a simplification of human-exoskeleton interaction through a one-degree-of-freedom system. F_{input} represents the force developed by the exoskeleton. Considering the displacement (x) that this force provokes and the stiffness value of soft tissues (k), F_{spring} represents the force absorbed by the human limb. The parameters of the system are also shown in Fig. 1: the inertia (I), the mass (m) and center of mass of the exoskeleton, the position of the cuff (L) and the imposed trajectory (Θ) of the robotic joint. Thus, the 2-dimensional model represents the forces developed in the sagittal plane of motion.

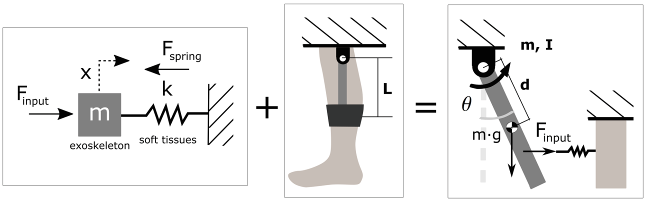

Fig. 1. The human-exoskeleton interaction model is composed by a one-degree-of-freedom system and a single-actuated-joint exoskeleton with a human shank.

2.2 Equations

Assuming the deformation angle of the linear spring is a negligible value, the input trajectory (Θ) is defined as a low amplitude sinusoidal signal. We consider this trajectory, the inertia of the system and gravity and obtain the input force of the one-degree-of-freedom model (Fig. 1). The following equations can be derived to characterize the dynamic behaviour of the system:

$$F_{input} = \left[\left(-m \cdot g \cdot d \cdot \sin\theta - I \cdot \frac{d^2\theta}{dt^2}\right)/L\right] \cdot \cos\theta \tag{1}$$

$$F_{input} - F_{spring} = m \cdot \ddot{x} \tag{2}$$

$$F_{spring} = k \cdot x \tag{3}$$

$$P_{spring} = F_{spring} \cdot \dot{x} \tag{4}$$

In which Eq. (1) describes the horizontal projection of the force developed by the structure of the exoskeleton, Eq. (2) represents the dynamic behaviour of the system, Eq. (3) describes the output force developed by the spring due to deformation length (x) from its equilibrium position and Eq. (4) represents the power developed by the spring.

3 Results

The previous equations are solved with defined parameter values (see Table 1) using Matlab. Stiffness value of soft tissues (k_2) was assumed from the experimental tests developed by Frauziols et al. [4].

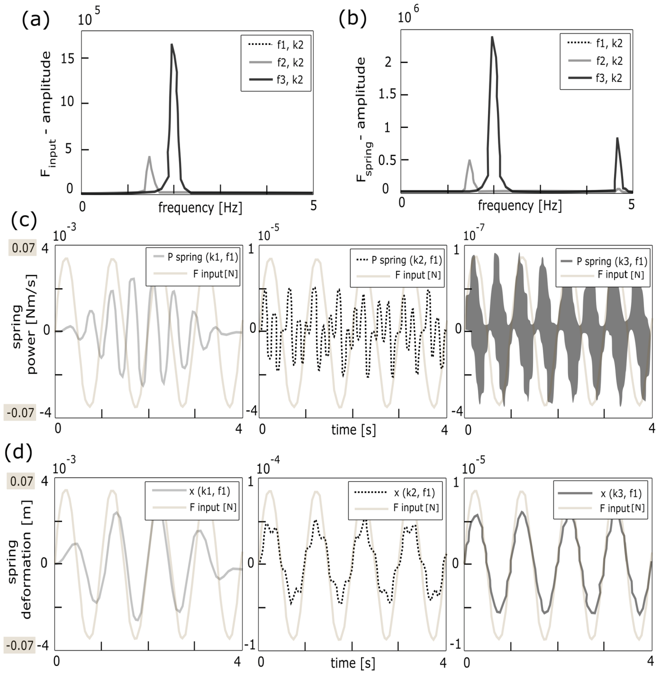

Fig. 2. (a) Frequency response of the input force developed by the exoskeleton and transmitted to the one-degree-of-freedom system. (b) Frequency response of the force developed by the spring with k_2. (c) Power developed by the spring and (d) spring deformation considering k_1, k_2, k_3 and f_1.

As shown in Fig. 2(a), we computed the frequency response for the input force developed by the exoskeleton, for f_1, f_2, f_3 for the sinusoidal input trajectory (Θ). In Fig. 2(b), for each frequency, the fundamental frequency, resulted from the input force of the system, and the first harmonic, that characterizes the behavior of the spring, are shown. The highest amplitude values in both Fig. 2(a) and (b) correspond to the fundamental frequencies with f_3 ($1.66 \cdot 10^6$ and $2.41 \cdot 10^6$). In Fig. 2(c) and (d) the spring power and the spring deformation are shown for k_1, k_2, k_3 when the joint of the exoskeleton performs the sinusoidal input trajectory (Θ) with the frequency value of knee joint during flexion while walking (f_1) [5]. Maximum spring power values are $2.61 \cdot 10^{-3}$ Nm/s, $2.10 \cdot 10^{-5}$ Nm/s and $3.66 \cdot 10^{-7}$ Nm/s while maximum spring deformation values are $2.74 \cdot 10^{-3}$ m, $5.06 \cdot 10^{-5}$ m and $6.03 \cdot 10^{-6}$ m corresponding to k_1, k_2 and k_3 respectively.

4 Discussion

With the results shown in Fig. 2 the role of soft tissues in force transmission can be argued. The cuff of the exoskeleton interacts with tissues of variable stiffness values because human topography is non-continuous and non-homogenous. Deformation values are higher at human limb locations where the tissues are softer while the absorbed power of these tissues also increases (see Fig. 2(c) and (d)). As a result, force transmission from the exoskeleton to the user's joint can depend on the position of the cuff due to the stiffness of the tissues it covers. In the performed simulations of the model, we considered a soft tissues stiffness value from experimental results [4] and two more values, lower and higher, which are constant.

Table 1. Model parameters

Parameter	Value
m	1.6 kg
I	0.05 kgm^2
d	0.13 m
L	0.26 m
k_1, k_2, k_3	100 N/m, 1400 N/m, 10000 N/m
f_1, f_2, f_3	1 Hz, 1.5 Hz, 2 Hz
Θ	$0.09 \sin(2\pi ft)$ [rad]

The frequency of input trajectory also affects the forces developed by the system. Thus, the movement the exoskeleton will assist and its control strategy have to be considered in order to obtain an efficient force transmission. We considered typical human walking frequency; however, tests with higher frequency values are interesting for the study of the stability of the system.

5 Conclusion

We have shown first results of the characterization of the behavior of soft tissues though a preliminary model of a simple system of single-actuated-joint exoskeleton and the human shank. Cuffs composed by materials of different stiffness values, depending on the stiffness value of the tissues they cover, could properly transmit forces from the exoskeleton to the human. Next steps will be: (i) validating the presented model through experimental tests, where the force of the spring will be measured with a load cell, (ii) including more realistic linear and non-linear stiffness values, considering different values for cuffs and human soft tissues, (iii) including damping (it was not considered yet due to the simplicity of the model), and (iv) consider dynamic situation when the shank of the subject is free to move and study the implications for control purposes.

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