Poster: Evaluation of a new control law improving the transparency of an exoskeleton

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I. Introduction

In recent years, powered exoskeleton-type assistive devices have become widely available as they may help injured or disabled people for recovering and make them more independent in their daily living activities. They could also be helpful to prevent the development of work-related musculoskeletal disorders [2]. However, the possible industrial and medical applications of these devices are challenged by the evidence of an average thirty percent movement slowdown when wearing a ”transparent” exoskeleton [1] which can result in a critical decrease in productivity or in unwanted side effects in the rehabilitation protocols.

This lack of concrete usability might be related to the fact that current exoskeletons are not designed with the prospect of establishing a symbiotic interaction between human and exoskeleton. Recent research has been more focused on the response of humans wearing an exoskeleton [4]. Reducing the unwanted impacts of wearing an exoskeleton is a crucial step towards a more symbiotic interaction. This could be achieved by improving the transparency of these devices. Despite the impossibility of reaching a perfect transparency, reducing the interaction forces is a necessary prerequisite in most applications.

We hypothesize that a strict direction-dependent identification of the robot, may improve transparency. Indeed, direction-dependent models allow to duplicate the number of parameters to describe behaviours that are not explained by rigid body dynamics [6]. This identification-based approach is complementary to solutions based on machine learning or interaction identification [5]. In the current study, the results of an accurate identification procedure are used to develop purely compensatory control laws. Their impact on human motor control is then studied in comparison with a standard closed-loop position control and by computing pre-existing performance indices [3]. Finally, a new performance index, which aims to quantify transparency through a ratio between electromyographic activity (EMG) and joint acceleration, is introduced and used to qualify the different control laws.

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II. Identification methodology and results

a) Methodology: This study focuses on movements of elbow flexion/extension as these movements have been abundantly described in the motor control literature [1]. This reduction to well-known movements is convenient to quantify the impact of wearing the exoskeleton, here an ABLE exoskeleton, and therefore, its transparency. Consequently, the identification methodology developed in this study is only applied to the robot elbow joint. The identification is conducted thanks to the current and position sensors of the robot and an optoelectronic system. This system is composed of eight infrared cameras and 3 mm reflective markers placed on the robot, which are used to estimate the position of an ABLE non-motorised slider added to reduce hyperstatic constraints. The identified model is given in Equation 1.

$$\mathcal{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathcal{C}(\mathbf{q},\dot{\mathbf{q}}) + \mathcal{G}(\mathbf{q}) + sign(\dot{\mathbf{q}})\tau_C + \nu\dot{\mathbf{q}} = \tau_{\mathbf{m}} \quad (1)$$

where $\mathcal{M}(\mathbf{q})$ represents the inertial terms, $\mathcal{C}(\mathbf{q},\dot{\mathbf{q}})$ represents the Coriolis/centripetal terms, $\mathcal{G}(\mathbf{q})$ represent the gravitational torques, τ_C represents the Coulomb dry friction torque, ν represents the viscous friction coefficient, $\tau_{\mathbf{m}}$ represents the actuators torques, $\mathbf{q}$, $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}}$ represents the joint positions, velocities and accelerations respectively.

The identification methodology is a step-by-step procedure. The first step is static, the second step is conducted at constant speed and the third step is a pseudo-sinusoidal excitation. As ABLE is a highly reversible and flexible robot, the identification is dissociated in two sets of all parameters, one for upward and one for downward movements.

III. Experimental validation

A. Task description

a) Participants: Six healthy right-handed young adults naive to the purpose of the experiment participated in these trials. Written informed consent was obtained from each participant as required by Helsinki declaration. The ethical committee for research (Université Paris-Saclay, 2017-34) approved the experimental protocol.

b) Task: Point-to-point reaching movements are performed through elbow flexion-extension in the sagittal plane. Targets are displayed on a large screen in front of participants and a red point representing the participant's current position in real time is computed through the optoelectronic system. The task is composed of five amplitudes of movement and four conditions. For each condition, 10 upward and 10 downward movements per amplitude are carried out. One condition is carried out outside of ABLE and is used as a control trial. A splint is given to the participants to immobilize their wrist and improve the interaction [4]. The electromyographic (EMG) activities of biceps brachial, brachio-radialis, triceps brachial lateral head and triceps brachial long head are recorded.

c) Control laws: Three control laws are tested. The first law is a classical closed-loop position control. In the second law, the friction is not compensated. The third law achieves a complete compensation of the identified dynamics. The second and third laws are purely compensatory open-loops.

d) Data processing and statistical analyses: Angular velocity and acceleration are obtained by numerical derivative of the positions measured by the optoelectronic system. Movements are cut at 5% of their maximal velocity. For each subject and each muscle, EMG signals are normalized regarding to their maximal measured value.

Inter-conditions differences are analysed with Friedman non-parametric statistical tests and post-hoc comparisons are conducted using Nemenyi tests. All levels of significance are set at $p < 0.05$.

B. Transparency assessment

The transparency of the tested laws is evaluated on the basis of pre-existing indices [3]. These indices describe global kinematic characteristics of the movement such as duration, maximal speed or curvature.

These indices cannot describe the transmission yield between the motor command and the resulting acceleration. Nevertheless, it is crucial to know how the wearing of the exoskeleton impacts this yield. In addition, the maximal acceleration is a good indicator of the movement plan. A new index is therefore defined as the ratio between the agonists' Root Mean Square activation and the maximal acceleration. This index is called "EMG/Acc".

IV. Results and Discussion

a) Conclusion on pre-existing indices: Overall, the three implemented laws can be qualified of transparent because they preserve classic features of the human movement. The law based on complete compensation of the dynamic model showed no significant difference on maximal velocity and movement duration in comparison with the control condition, thereby resolving the motion slowness mentioned in the introduction.

b) EMG/Acc: The mean results show an improvement of the muscular activation/acceleration yield with the use of the complete compensation law compared to the two other laws (see Figure 1). The closed-loop position control law is the least transparent according to this index. Significant differences appeared between the conditions ($p < 0.01$) and the post-hoc showed a significant difference between the complete compensation law and the closed-loop position control law ($p < 0.01$). This confirms that the complete compensation law reaches a greater level of transparency than the other two laws on average.

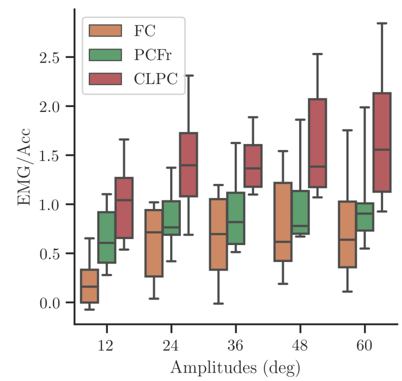

Fig. 1. Agonist muscle transparency index for the different conditions and for upward movements. **FC:** Full Compensation based on identification. **PCFr:** Partial Compensation based on identification without Friction compensation. **CLPC:** Closed-loop position control.

V. Conclusion

This study aimed to improve the transparency of an ABLE exoskeleton. The transparency increased by using a direction-dependent model to identify and by using a control law compensating the whole identified dynamic model. Experimental tests conducted on six participants and three transparent laws showed a significant amelioration of transparency by following this procedure.

In order to describe more accurately the level of transparency reached by the proposed control law, a new performance index is introduced. This index reflects the yield between the level of EMG activity and maximal acceleration of the limb and is adaptable to other movements than the flexion/extension of the elbow. This index seems to be a reliable indicator of the movement transparency when interacting with an exoskeleton as it is a good indicator of the movement plan.

If generalized, the transparent law obtained during this study could be used as a basis to study human motor control when wearing an exoskeleton.

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