Improving and quantifying the transparency of an upper-limb robotic exoskeleton with a force sensor and electromyographic measures

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1. Introduction

Powered exoskeletons are a promising tool in order to prevent work-related musculoskeletal disorders and assist people with motor deficiency (Ajoudani et al. 2018). However these devices are still suffering from a lack of acceptability partly related to their direct influence on human motor control, which can induce motion slowness or lack of comfort.

When an exoskeleton does not affect human movement, it is said 'transparent'. This condition is mainly theoretical as it is quite impossible to realize in practice since human motion cannot be fully predicted (Jarassé et al. 2008). However, getting as close as possible to a perfect transparency is important to optimize human/robot (HR) interaction. This may be achieved through the design of more efficient, dedicated control laws.

In a previous study, the influence of three different control laws implemented on an upper-limb exoskeleton has been analyzed (Verdel et al. 2021). These laws were: (i) a closed-loop position control (CLPos), (ii) an open-loop torque control based on an identification procedure without friction compensation (PC), (iii) an open-loop torque control with full compensation based on an identification procedure (FC). The latter control law was found to be the most transparent. These data have been used as a comparison basis for the current study which aims at improving transparency, by closing the loop with data from a force/torque (F/T) sensor and by designing an ergonomic HR interface.

2. Exoskeleton control

The control of the exoskeleton is primarily based on an accurate identification of its dynamic parameters, allowing to build an open-loop control as described in Verdel et al. (2021). In the present study, the main contribution is the addition of a F/T sensor between the human and the exoskeleton forearms. This sensor allows the construction of a feedback loop to compensate for identification errors and to minimise interaction efforts (CLζ? control law). This feedback loop uses a proportional-integral corrector, thereby resulting in the control scheme presented in Figure 1.

3. Methods

3.1. Participants

29 participants (14 women) took part in the experiment. Their age, height and weight were respectively 23.2 ± 2.9 years, 174.7 ± 7.5 cm and 67.1 ± 11.6 kg. All were right-handed and naive to the purpose of the experiment. Written informed consent was obtained from each participant.

3.2. Materials

As in our previous work (Verdel et al. 2021), the ABLE upper-limb exoskeleton was used in the present experiment. The HR interface has been modified in the process. The interaction surface has been increased and the overall comfort has been improved by substituting the classical attachment with a flexible thermoformed part moulded on the basis of a human forearm. In order to minimise unwanted interaction efforts, a passive ball joint has been placed between this moulded part and the exoskeleton, thereby following recommendations of Jarrassé et al. (2012). The angular positions of the elbow were computed from recordings with the Qualisys™ motion capture system. Muscle activity was recorded with four EMG sensors (Cometa) placed on flexors (brachio-radialis and biceps brachii) and extensors (triceps long and triceps lateral heads) following SENIAM recommendations.

3.3. Procedure

Participants performed elbow flexion-extension movements in the sagittal plane with and without the exoskeleton, at their preferred velocity. Their arm was held stationary at the side of the body, their back leaning on the exoskeleton's rigid base. Movements towards two targets, placed vertically in front of participants at 30° above and 30° under the horizontal, were performed. The targets had to be reached in a single one-shot movement. Only upward movements were considered in the present study because downward movements were too slow to exploit the performance index defined below. A pause of random

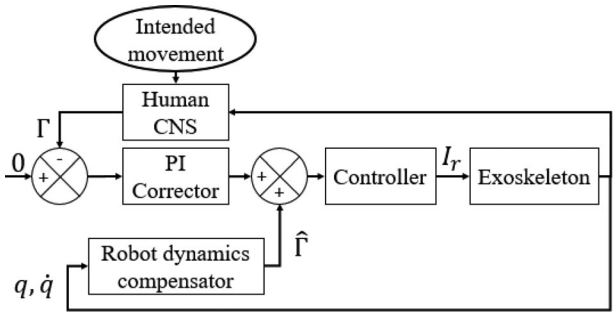


Figure 1. Control scheme of the transparent control law. r is the interaction torque computed at the level of the joint based on the F/T sensor, $\hat{r}$ is the evaluated dynamic compensation torque and I_r is the resulting motor current.

duration (one to two seconds) was imposed between each movement.

3.4. Data processing

The angular velocity and acceleration were computed by numerical differentiation of the recorded position signal filtered at 5 Hz (Butterworth, low-pass). The root mean square (RMS) of the EMG signal was computed over the movement duration on the rectified and filtered EMG signal (band-pass, Butterworth, 20–450 Hz). The beginning and end of movements were detected when the elbow's angular velocity was above 5% of the maximum velocity. The index called EMG/Acc (see Verdel et al. 2021 for details) was computed. This performance index can be seen as an efficiency between muscle activation (input power) and maximum acceleration obtained (output power). This value is then normalised by the value obtained during similar movements outside the exoskeleton. As a result, the closer the value obtained is to zero, the closer the control is to perfect transparency according to the EMG/Acc index.

3. Results and discussion

The movements performed by the subjects in this study correspond well to normal human pointing movements with bell-shaped velocity profiles. Furthermore, the mean absolute normal interaction force measured during the present experiment was $F_i = 1.54 \pm 0.63\ N$ which is of the same magnitude as in other studies (Jarrassé et al. 2008) (Figure 2).

Comparing the ratio between muscle activity and peak acceleration (EMG/Acc) of the F/T sensor feedback control with previously studied laws suggests an improvement in terms of transparency as the index isindeed closer to zero. This means that for the same amount of muscle activation, the acceleration produced is higher, thus the exoskeleton would be less resistant. This improvement can be due to a better

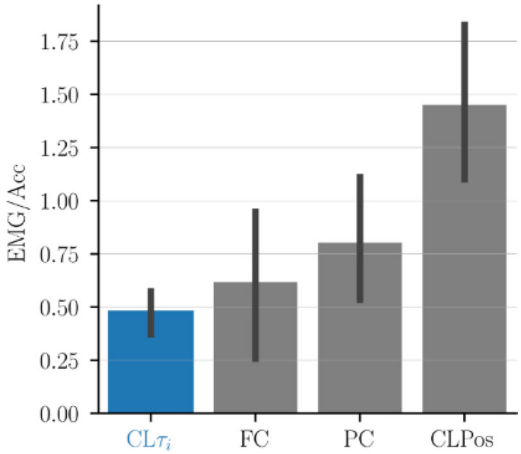


Figure 2. The EMG/Acc index calculated for the CLr_i law (in blue) is compared to the laws of our previous study (Verdel et al. 2021) for 60 degrees upward movements.

compensation of the inertial effects achieved by the feedback on interaction efforts, a compensation of the identification errors, and/or an improved physical interface. Nevertheless, no statistical difference was observed between the best previous condition, FC, and the current condition, CL$\zeta_?$ (Mann-Whitney, $p = 0.24$). This is probably due to the limited number of participants in the FC condition ($n = 6$ in Verdel et al. 2021). Moreover, in the absence of human movement prediction features, the control still lags behind the user and the inertia cannot be fully compensated as mentionned in Lamy et al. (2009).

4. Conclusions

The present preliminary study suggests that the use of a F/T sensor and interfaces including passive degrees of freedom can improve ABLEs's transparency. However, a study comparing the different laws and interfaces on the same individuals is needed to conclude. These comparisons and the integration of predictive controls will be the subject of future work, as well as the use of non-zero desired torques, in the case of load carrying tasks for example.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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