Controlling robotic assistive devices with natural body compensations

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The loss or the impairment of the upper limb is highly incapacitating. To recover some autonomy and independence, disabled people may be offered robotic assistive devices. For example, people with cerebral palsy or spinal cord injury can use exoskeletons, and robotic prostheses allow the restoration of amputees' motor capabilities. However, giving a natural and efficient control of these devices is still one major challenge [1]. Indeed, although great improvement was observed through the development of various wearable mechatronic devices with multiple degrees of freedom (DOF), such as in [2], the control stage often remains a limiting element.

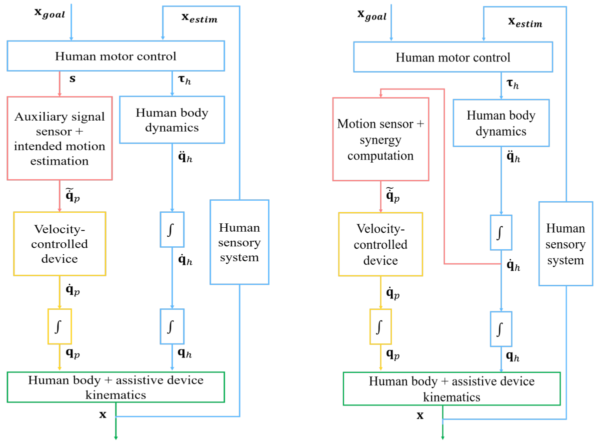
We propose here to analyse in details how the choice of the input signals of the robotic control schemes can impact the user motor behaviour. We point out that these alterations usually lead the user to exhibit body compensations, and then propose a new closed-loop control scheme based on these compensatory movements. This novel approach does not interfere with the user motor control loop, and could lead to a more efficient control of assistive devices.

I. ANALYSIS OF THE MAIN CONTROL SCHEMES

A. "Direct connection" control

Most control approaches use a direct connection between an auxiliary signal produced by the subject and the resulting movement of the assistive device generated by the controller (see Figure 1(a)). The auxiliary signal is typically a physiological signal (electromyogram for instance) [3] or the movement of another joint [4]. In Figure 1(a), it is clear that this approach create two parallel processes: (i) the natural human body dynamics (in blue) and (ii) the generation of the auxiliary signal leading to the device motion (in red and yellow). The user has thus to deal with two commands, the one of his/her body and the one of the device. A simple motion is actually transformed into a difficult double task, which consists in simultaneously generating the auxiliary signal to move the robotic joints and completing this motion with the motion of the healthy human joints.

Despite the mental burden and the necessary training, this could be manageable if the generation of the auxiliary signal was as fast as the body dynamics process, but this is rarely the case. The control of the robotic joints is thus much slower and less reliable than the control of the human joints. Users of assistive devices often choose to preferentially command their body dynamics when performing a desired motion, at the expense of the device active property. They first exploit the one of the two processes that allows a faster and more reliable movement, but this lead them to exhibit body compensations [5].



(a) "Direct connection" (b) Joint synergy-based control

Fig. 1: Diagrams of the main control schemes. (a) "Direct connection": main stream approach in assistive device control. The human subject is asked to control the robotic device by the generation of auxiliary signals. (b) With a joint synergy-based controller, only the body movement is used to generate synergetic device motion.

B. Synergy-based control

Alternative solutions have been explored to avoid asking subjects to generate an extra signal independently from the control of their healthy joints. They consist in observing the motion of the healthy body and then to deduce the completing motion of the device ([6], [7] e.g.). The input signal of the controller, the kinematic measurements of the body motion, does not interfere with the natural motor control loop of the subject (see Figure 1(b)). There are not two processes in competition and the user has to deal with a single process: his/her body dynamics. This approach thus seems more appropriate and much easier to learn and use that the direct connection approach. However, the completing motion of the assistive device is deduced from healthy joints motion with models of the synergies and these models are not yet fully accurate. Prediction errors can occur, which requires a

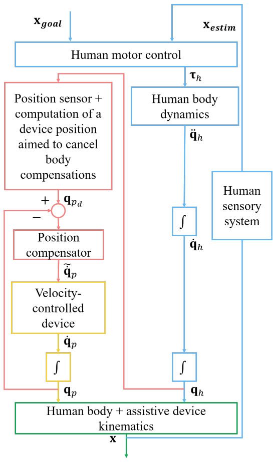


Fig. 2: Diagram of Compensations Cancellation Control.

correction step by the user, a correction mainly achieved with body compensations [7].

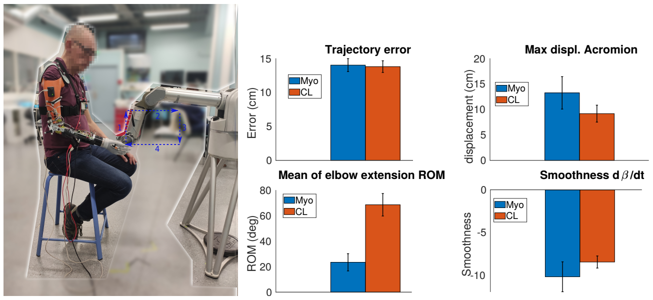
II. COMPENSATIONS CANCELLATION CONTROL

A. *Concept*

The previous analysis of how the main control approaches work points out that, whatever the approach used, disabled users exhibit body compensations. This is not new since many studies have considered this problem. Yet, compensatory motions are only taken into account to evaluate the performance of the approaches (see [8]). We rather propose to use these motions as input of a control scheme (see Figure 2). It operates in three steps: (i) analysis of the body posture to evaluate whether the subject is currently compensating for an inadequate device configuration; (ii) when a body compensation is detected, computation of a new desired position of the device, to cancel this compensation; (iii) servoing the robotic joint positions to this desired value with a secondary loop. This scheme, later called Compensations Cancellation Control (CCC) does not disturb the natural motor control loop of the user and no final step of error correction is required as body compensations are themselves the input of the controller. We also assume that, as postural compensations are naturally employed by the Central Nervous System, the user would not need a specific learning phase and could even master the control of the device without any previous knowledge on the concept.

B. *Experimental application for the control of a prosthetic elbow joint*

To validate the feasibility of CCC on a real case, we performed an experiment where CCC was implemented on an upper-arm prosthesis. A congenital arm amputee executed a path-tracking task (see Figure 3(a)), while controlling his prosthetic elbow either with CCC or with his conventional myoelectric control (MYO). Figure 3(b) shows the metrics used to compare MYO and CCC. The trajectory error evaluates whether the task is correctly performed, which is the case for both MYO and CCC (the trajectory error is similar). The ROM of the acromion evaluates the amount of compensations and shows that it is higher with MYO than with CCC. The ROM of the elbow indicates that, with MYO, the subject underused the prosthetic elbow and prefered to use body compensations to move his hand. This confirms what was stated in Section I: the subject does not preferentially use MYO to bring the hand to a desired position, but rather uses body compensatory motions. The smoothness metric is also in favor of CCC, as elbow angular velocity is smoother than with MYO.



(a) (b)

Fig. 3: Experimental validation of CCC. (a) Experimental set-up. (b) Results of the path-tracking task performed by the amputee participant.

The concept of CCC is thus valid to control a prosthetic elbow joint. It seems to be as performant to realize a task as conventional myoelectric control but more natural in terms of kinematics and smoothness. Future works will aim at extending CCC for the control of other prosthetic joints, like the wrist, or even for a simultaneous control of several prosthetic joints, but also at extending validation to other assistive devices, like upper-limb exoskeletons.

ACKNOWLEDGMENT

This work was supported by ANR BYCEPS, ANR-18-CE19-0004 and has been sponsored by the French government research programm *Investissements d'avenir* through the Robotex Equipment of Excellence (ANR-10-EQPX-44).

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