Interacting with a ”transparent” upper-limb exoskeleton: a human motor control approach

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Abstract— **Establishing a symbiotic relationship between a human and a exoskeleton is the end goal in many applications in order to provide benefits to the user. However, the literature focusing on the human side of human-exoskeleton interaction has remained less exhaustive than the literature focusing on the design (hardware/software) of the exoskeleton device itself. It is, though, essential to understand how a human adapts his motor control when interacting with an exoskeleton. Motor adaptation is an implicit process carried out by the central nervous system when the body encounters a perturbation, a paradigm that has been extensively studied in the field of human motor control research. When wearing an exoskeleton, even "as-transparent-as-possible", contact/interaction forces may impact well-known motor control laws in a way that may be detrimental to the user, and even compromise usability in real applications. The present paper investigates how interaction with a backdrivable upper-limb exoskeleton (ABLE) set in "transparent" mode of control affects the kinematics/dynamics of human movement in a simple task. We find that important motor control features are preserved when moving with ABLE but an overall movement slowness occurs, likely as a response to increased inertia according to optimal control simulations. Such a human motor control approach illustrates one possible way to assess the degree of symbiosis between human and exoskeleton, i.e. by grounding on well-known findings in motor control research.**

I. INTRODUCTION

Exoskeletons are promising devices for rehabilitation, assistance, prevention and human performance augmentation. Exoskeleton research has primarily focused on hardware/software development in order to create state-of-the-art controllers aiming, for instance, at making the exoskeleton more "transparent" to the end user, or at reducing metabolic energy expenditure in fatiguing tasks [1], [2]. This initial and necessary engineer-centered phase in exoskeleton research is now being complemented by more human-centered approaches [3]. The rationale is that human response to interaction with an exoskeleton is a critical feature of Human-Exoskeleton Interaction (HEI) but it remains poorly known. In particular, understanding how human adapts to an exoskeleton device and how this interaction modifies their natural motricity is critical to improve their effectiveness [4]. In neurorehabilitation, this lack of knowledge may partly explain why exoskeletons still barely outperform conventional therapies [5]. Our approach is thus to analyze the extent to which wearing the upper-limb exoskeleton ABLE [6] affects the human motor controller. We focus on one of the most favorable cases, which is the transparent control, and rely on a simple task for which fundamental motor control principles have been thoroughly documented, i.e. single-joint pointing movements.

Several recent studies have addressed the question of how humans adapt their nominal motricity during HEI. A common way to investigate this kind of issue is to ask an healthy subject to perform goal-directed movements with and without the exoskeleton set in a transparent control mode, and use standard metrics to quantify human motor performance. Transparency is classically defined as a mode of control that does not modify the nominal behaviour of the user in terms of end-effector, joint trajectories and patterns of muscle activations [7]. Theoretically, complete mechanical transparency would be attained if there is no interaction force between the human and the exoskeleton, but it is practically impossible because the movement of the human user is not fully predictable and both kinematic chains cannot match perfectly. Yet, the very presence of an external contact with a tool may involve different control strategies (e.g. see [8]). Concerning upper-limb 3D pointing tasks, it has been previously shown that wearing a transparent exoskeleton induces different muscular coordinations [7] and different movement kinematics [3]. In particular, subjects moved slower with the exoskeleton even though they were able to move faster when instructed to [3], [9]. These studies investigated 3D reaching movements and involved many degrees of freedom (DoF) at the shoulder, elbow and/or wrist for which complex nonlinear phenomena may occur, including the exoskeleton structure itself. This actually contrasts with an important part of the human motor control literature, which has extensively focused on simpler movements involving 1 or 2 DoF (single-joint or planar movements). Notably, an interesting set of studies has focused on how human adapts to external perturbations induced by a mechanical manipulandum during planar arm reaching movements. In such protocols when predictable perturbations were induced by the robotic device, participants generally returned to their nominal behaviour by canceling the effects of the novel environment, although this may be a non-optimal strategy from an energetic viewpoint [10], [11]. On a longer time scale, a re-optimization process could arise [12] and a reduction of metabolic expenditure through motor adaptation was also observed [13]. For unpredictable perturbations, however, an energy-consuming strategy (muscle co-contraction) was used by human subjects to counter the effects of a divergent/unstable force field

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[1] CIAMS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France name.surname@u-psud.fr

[2] CIAMS, Université d'Orléans, 45067, Orléans, France

[3] Institut Universitaire de France, Paris, France

[4] CEA, List, Interactive Robotics Laboratory, 91191, Gif sur Yvette, France name.surname@cea.fr

[14]. More familiar perturbations were also studied such as wearing an object/load in the hand. In this case, adaptation appears to be almost immediate [15]. When the load is modified, motor strategy stabilizes in such a way that, with increasing load, movement velocity decreased and duration increased by the same factor.

Besides motor adaptation studies, several studies have investigated whether basic principles could underlie normal motor control. In this paper, we will rely on two well-documented motor control principles. First, the "isochrony principle" states that humans spontaneously increase the velocity of their movement as a function of distance to be traveled, so as to keep duration approximately constant [16] (actually duration also increases with distance for large enough movements [17]). Second, the "law of asymmetries" states that acceleration time is systematically longer for downward movements compared to upward ones of similar duration [18]–[20]. Both fundamentals can be derived from optimality principles of human motor control. The first one might originate from a tendency in human to plan movement by trading-off the physical cost of movement with a cost of time [17], [21]. The second one may be due to the optimal integration of gravity in movement planning [19], [20]. This non-exhaustive list of motor control principles highlights the existence of preferred and robust strategies in unperturbed/nominal motor control, which can thus be used as a comparison basis in HEI studies.

Knowledge in human motor control thus suggests that the impact of wearing an exoskeleton, even a "transparent" one, may be non-trivial and could affect the optimality of human motor behavior. Hence, we deliberately focus on basic movements, well-documented in motor neuroscience, to analyze the extent to which the perturbation introduced by the ABLE exoskeleton modifies known human movement strategies.

II. Methodology

A. Experimental task and materials.

Eighteen healthy participants (mean age, height and weight: 24.3±5.0, 177.4±9.8 cm, 71.4±13.0 kg, respectively) participated in this study. Written informed consent was obtained from each participant in the study as required by the Helsinki declaration and procedures were approved by the ethical committee for research (Université Paris Saclay, 2017-34). The backdrivable ABLE 7 DoF upper-limb exoskeleton was used in this experiment [6] but only forearm movements were investigated. Participants were asked to perform right-sided pointing movements involving elbow flexions/extensions (see Fig. 1). Elbow joint angle was measured using a wireless goniometer (Biometrics Ltd, UK), which had been validated through preliminary experiments using a motion capture device. Participants were instructed to move as naturally as possible such that the task was carried out in the most comfortable situation for the subject. To test the above-mentioned isochrony and asymmetry principles, 5 amplitudes (from 20° to 100°) and two directions (upward vs downward) were tested. Finally, two conditions were tested

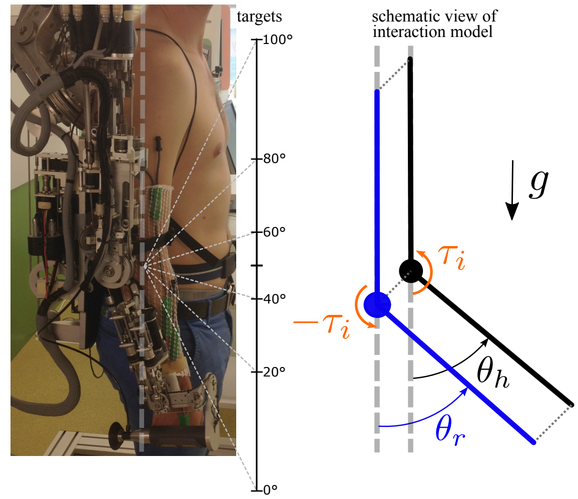

Fig. 1. Picture of the ABLE exoskeleton and illustration of the task. Left: lateral view of the exoskeleton and the participant. Targets and corresponding motion amplitudes are also reported. Right: schematic view of the interaction model between the exoskeleton and the human forearm.

to analyze the effect of moving with ABLE: with and without exoskeleton. The order of these conditions was randomized across participants. Each participant performed 100 distinct movements (5 amplitudes $\times$ 2 directions $\times$ 10 repetitions) in each condition, thereby yielding a total of 200 individual movements per subject.

B. Transparent mode and interaction model.

The transparent control law used to drive the exoskeleton was defined as follows:

$$\tau_r = \hat{b}_r\hat{\dot{\theta}}_r + \hat{F}_{NL} + \hat{m}_r g \hat{l}_r \sin(\hat{\theta}_r) \tag{1}$$

where τ_r is the elbow axis torque generated by the robot, $\hat{\theta}_r$ and $\hat{\dot{\theta}}_r$ are the angular position and velocity estimated from the robot sensors. Parameters $\hat{b}_r$, $\hat{m}_r$ and $\hat{l}_r$ are the estimated axis specific coefficient of viscosity, mass and length to the center of mass of robot forearm respectively, and $\hat{F}_{NL}$ represents the estimated nonlinear friction in the joint. Thus in the present control mode, which was the default transparent mode, the robot compensated its own friction and weight but not its inertia (Eq. 1). During the interaction, human and robotic forearm dynamics are coupled, which can be modeled as follows:

$$\begin{cases} J_h\ddot{\theta}_h + b_h\dot{\theta}_h + m_h g l_h \sin\theta_h = \tau_h + \tau_i \\ J_r\ddot{\theta}_r + b_r\dot{\theta}_r + F_{NL} + m_r g l_r \sin\theta_r = \tau_r - \tau_i \end{cases} \tag{2}$$

where τ_i is the interaction torque between human and robot limbs, and J stands for moment of inertia. The subscripts r and h denote similar quantities related to robot and human systems, respectively. If all estimated quantities in Eq. 1 are accurate, the interaction torque perturbing the human limb can be approximately evaluated as $\tau_i \approx -J_r\ddot{\theta}_r$ (substituting τ_r in Eq. 2 with its expression in Eq. 1). Further assuming human and robot joint angle accelerations are equal ($\ddot{\theta}_h = \ddot{\theta}_r$), the equation of motion of the human limb would simplify, in first approximation, as follows:

$$(J_h + J_r)\ddot{\theta}_h = \tau_h - b_h\dot{\theta}_h - m_h g l_h \sin(\theta_h) \qquad (3)$$

These theoretical considerations illustrate that the effect of moving with ABLE in transparent mode, should mainly be equivalent to an increase of inertia and a change of the inertial torque as seen in Eq. 3. This approximate derivation suggests that the perturbation could be analog to an increase of inertia without gravitational torque modification (which is a somewhat unusual situation) but the changes induced by the interaction may be even more complex in practice.

C. Data analysis and movement parameters.

We used standard motor control procedures and parameters to process and analyze data as detailed below. Statistical analysis was conducted using two-way repeated-measures ANOVA (first factor was up/down, second factor was with/without) and paired t-tests. A significance threshold of 0.05 was adopted for the statistical analysis. Linear regressions were also applied to fit relationships between parameters of interest and movement amplitudes, especially when investigating the "isochrony principle".

Kinematic analysis included the following parameters: movement duration, mean velocity, and relative time to peak velocity (TPV), which is defined as the ratio between acceleration duration and total movement duration. A TPV parameter equal to 0.5 means that the underlying velocity profile is symmetrical in the sense that acceleration and deceleration phases have the same duration. To investigate upward versus downward asymmetries in velocity profiles, we defined an index of asymmetry computed as follows:

$$Asym = TPV_{downward} - TPV_{upward} \qquad (4)$$

In absence of asymmetry between upward and downward movements, then $Asym = 0$. In previous studies dedicated to vertical arm movements, $Asym$ was found to be positive (e.g. see [19]).

An inverse dynamic analysis was performed using Eq. 3. We estimated anthropometric parameters for each participant using documented tables [22]. The viscosity coefficient b_h was chosen based on previous studies and set here to 0.05 [23]. Subsequent computed parameters were: the integral of the absolute value of the power at the elbow joint (also called absolute work in the following), and the integral of the square of net joint torque. All the above-defined parameters were computed for the effective movement phase, defined as the time interval for which angular velocity exceeded 5% of its peak value [3].

D. Predictive optimal control model.

We simulated the change of behavior during interaction with a simple optimal control model. Our goal was to focus on the expected overall movement slowness which may result from an increased moment of inertia when moving with ABLE. We initially assumed that an unperturbed human movement minimizes the following type of cost function [17]:

$$C(u) = \int_0^{t_u} \left(u^2 + g(t)\right) dt \qquad (5)$$

where $u = \dot{\tau}$ is the control variable (torque change, e.g. see [24]) and $\theta, \dot{\theta}, \tau$ are the controlled variables. The cost function has two parts: the term u^2 measures the physical effort of the movement according to the square of the control variable and the term $g(t)$ corresponds to a time-dependent cost that penalizes movement time independently of the actual arm trajectory (see [17] for details). This time-effort optimal control model defined in Eq. 5 is able to predict movement time given a movement amplitude as input, thus allowing to test the isochrony principle previously introduced. We shall focus on averaged up/down movement data, so that we neglect the effect of gravity here. This model notably predicts smooth bell-shaped velocity profiles as classically observed for this type of movement (see [24], [25]). As $g(t)$ can be estimated from experimental motion data without the exoskeleton, the nominal isochrony relationship can be deduced accurately. Assuming participants will plan their movements based on the same optimal control mechanisms, movement durations can be predicted when wearing the exoskeleton, i.e. in presence of a supplemental moment of inertia produced by the robot. Such a model will be used to help interpreting empirical observations.

III. RESULTS

A. Kinematic analysis.

Representative position, velocity and acceleration profiles are illustrated in Fig. 2. These results are in accordance with kinematic properties of goal-directed movements performed by healthy subjects (e.g. [26]). For instance, the smooth and bell-shaped angular velocity is a signature of a natural point-to-point movement. We observed that both velocity and acceleration magnitudes were clearly lower when wearing ABLE and that this was associated to a longer motion duration. Movement time was significantly higher when wearing the exoskeleton ($t = 17.7$, $p < 0.01$), when averaging movement times for all amplitudes and directions of motion. In these single-joint pointing movements, torque and power profiles directly matched kinematic variables.

B. Isochrony principle and law of up/down asymmetries.

Linear regressions were applied to amplitude-velocity relationships. While the linear increase of velocity with amplitude was preserved (large determination coefficients in both cases), the slope was significantly reduced when interacting with the exoskeleton (see Fig. 3a)[$F(1, 17) = 124.2$, $p < 0.01$], velocity being 30% slower with ABLE. Coefficients of determination indicated that the isochrony principle was qualitatively maintained in presence of the exoskeleton. Index of asymmetry analysis did not reveal any significant difference between movements performed with and without ABLE [$F(4, 170) = 1.14$, $p = 0.29$]. In

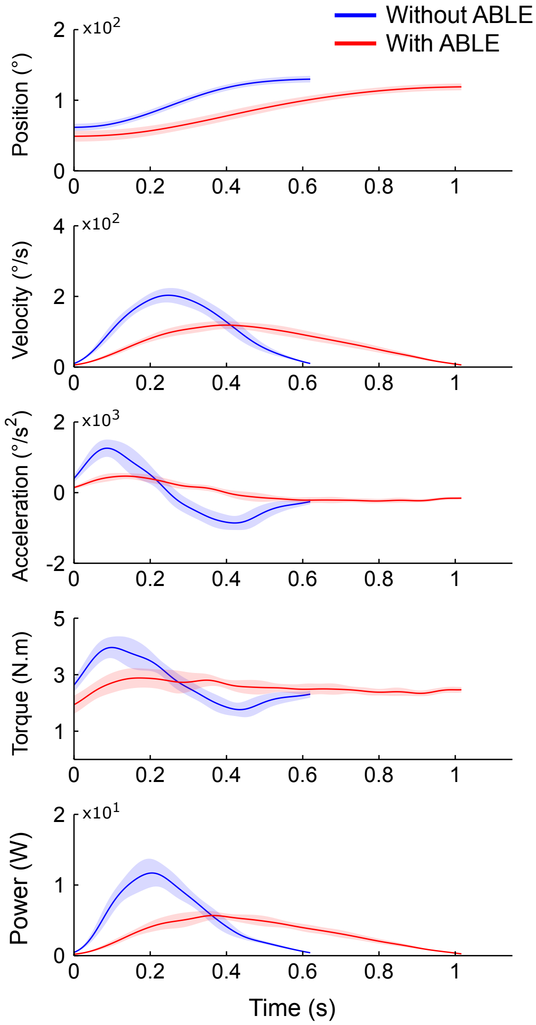

Fig. 2. Temporal evolution of kinematic and dynamic variables for a 60° upward movement. Solid lines represent the mean of 10 trials ($\pm SD$ in shaded areas) performed by a representative participant.

both conditions, this index was found to be positive (see Fig. 3b), reflecting the presence of significant upward versus downward asymmetries of velocity profiles, for all amplitudes. Despite an overall movement slowness, the isochrony principle and the law of vertical asymmetries still held when interacting with the exoskeleton.

C. Dynamic and energetic analysis.

Slopes of amplitude/absolute work relationships did not reveal any significant difference between condition with/without $[F(1, 17) = 0.66, p = 0.42]$. Initially, we might have expected a higher absolute work of joint torque due to the additional inertia induced by the exoskeleton. However, the overall movement slowness tended to compensate the theoretically larger inertial torque induced by ABLE. Because the work of gravitational torque only depends on movement amplitude, this means that the work of dynamic torque was the same in both conditions (Fig. 3c). In order to consider energy expenditure related to heat energy loss for gravity

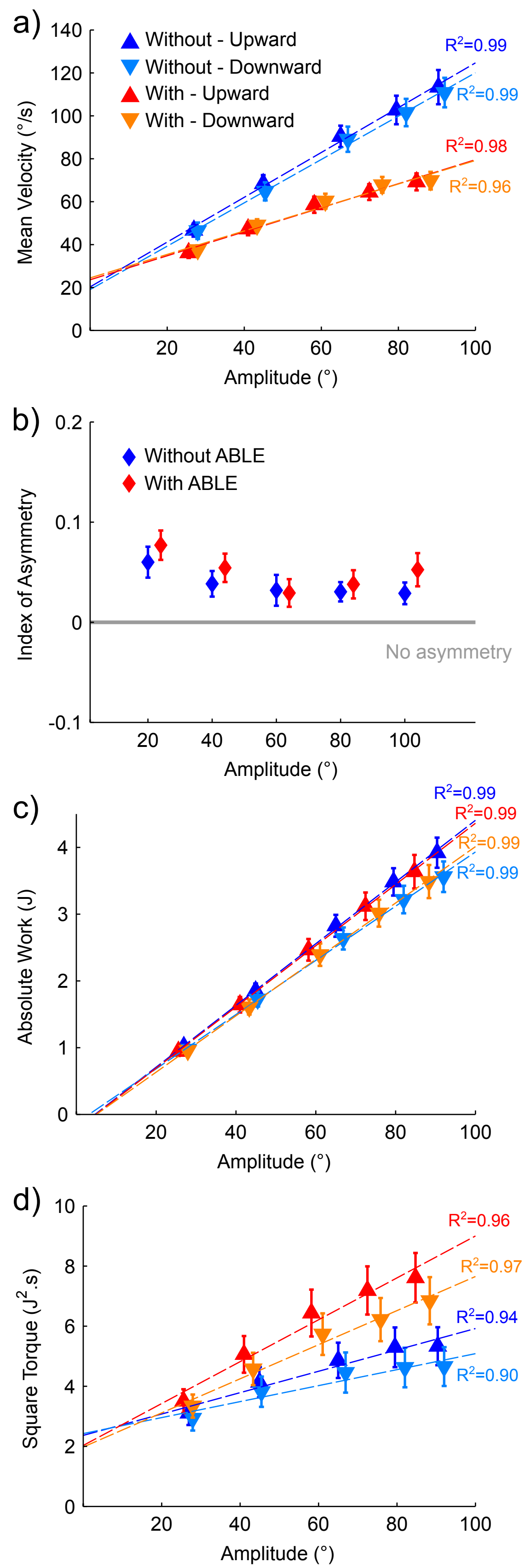

Fig. 3. Parameters of interest. a) Angular velocity; b) Index of asymmetry; c) Absolute work; d) Square torque all depicted as a function of movement amplitudes averaged for all participants (±SE). Dotted lines represent linear regressions with associated coefficients of determination (R^2).

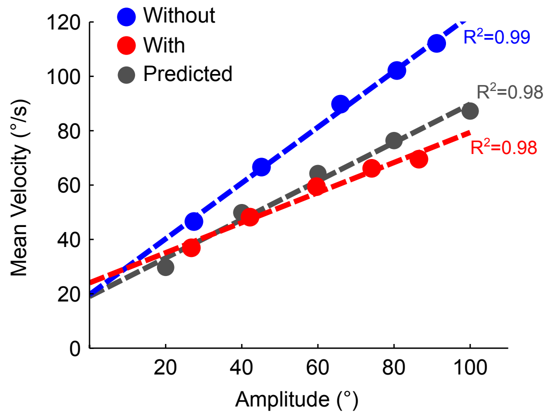

Fig. 4. Simulated amplitude/velocity relationship predicted with ABLE, computed from the time-effort optimal control model and experimental data averaged between directions. Dotted lines represent linear regressions of experimental data.

compensation, we also computed the sum of square torque (Fig. 3d). We found that moving with ABLE required a greater amount of square torque $[F(1, 17) = 49.8, p < 0.01]$. A main effect of movement direction was also exhibited $[F(1, 17) = 49.5,\ p < 0.01]$.

D. Explanatory model for overall movement slowness.

The amplitude/velocity relationship predicted by the time-effort optimal control model (Eq. 5) revealed the same trend than the experimental data with the exoskeleton. In particular, the determination coefficient (see Fig. 4) for predicted data was as large as the experimental one. It however seems that the model predicted slightly faster movements for large amplitudes, a discrepancy which is discussed below.

IV. Discussion

The aim of this study was to understand the effect of interacting with an exoskeleton on nominal human motor control. Previous research in movement neuroscience has described robust principles which are characteristic of simple 1-DoF or 2-DoF planar movements. Here we focused on the most simplified case of elbow flexion/extension. Goal-directed pointing movements have been analyzed under two conditions, namely with and without interacting with an upper-limb exoskeleton ABLE.

Clearly, wearing the ABLE exoskeleton was not transparent and altered even these simple movements. This is in accordance with previous studies using the same robotic device [3], [9]. The time to perform the task was significantly higher when wearing the exoskeleton and this difference increased substantially with motion extent. As a consequence, an overall movement slowness occurred, even for a simple elbow flexion/extension motion. We believe that this simple fact might have important consequences in terms of productivity and/or acceptability, in industrial or rehabilitation contexts. Our theoretical considerations nevertheless suggested that this phenomenon could be due to the additional inertia induced by the exoskeleton. This was supported by simulations performed with an optimal control model and partly expected from the motor control literature. Indeed, an increased inertia can be obtained by attaching a load to the arm/hand, which was shown to reduce movement velocity in human [15]. Yet, a load would vary inertial and gravitational torques proportionally. Here, wearing the exoskeleton does not modify gravitational torques on the human side as it would be the case if holding a load in the hand for instance. Interestingly, interacting with ABLE in transparent mode thus induced a somewhat non-ecological situation that should not have been encountered in daily life. Participants were however able to perform the task with little familiarization and good reproducibility across repetitions. Velocity profiles obtained in this study were maybe not important enough to involve large enough inertial torque compared to gravitational torque. It would thus be interesting to test faster movements in the future rather than self-paced movements.

Besides this major change in movement speed, several results are encouraging and show that interacting with ABLE did not break well-known motor principles. First, the "isochrony principle" was conserved in presence of the exoskeleton (although it was qualitatively changed), which indicated that the brain still increased speed as a function of distance (almost in an affine way for the range of amplitudes tested, except maybe for the larger amplitudes). Second, the typical up/down asymmetry of velocity profiles was found to remain the same. This could make sense as wearing the exoskeleton does not modify the weight of the human limb. This latter result may be seen as a proof of efficiency of the exoskeleton gravity compensation controller. As both fundamental laws considered here have been mainly conserved, our findings suggest that the kinematic properties of human movement were mainly re-scaled instead of completely altered in presence of the exoskeleton. It would be interesting in future studies to see whether people can improve further their movement efficiency with the exoskeleton and, in particular, whether they would keep moving slowly or increase speed with more practice.

From an energetic point of view, a trade-off seemed to appear between the increase of inertia due to ABLE and the decrease of velocity when wearing ABLE. On the one hand, additional inertia should increase the work and amount of dynamic torque. On the other hand, a reduction of velocity would decrease dynamic torque. Gravitational torque is particular in the sense that its work just depends on initial/final positions whereas acting against gravity nevertheless costs energy dissipated as heat. While wearing ABLE did not imply an increase of joint power on the human side, it still implied a greater total amount of integrated squared torque especially for large amplitudes (squared torque has been assumed to scale with heat energy loss, e.g. [27]). By extension, this should indicate that metabolic energy expenditure was higher when moving with ABLE in transparent mode. Whether or not participants could be able to reduce metabolic cost through more practice and learning is an open question. We note that moving faster to save heat energy loss due to gravity would necessarily increase the work of torque because of the supplementary inertia. Hence, it is quite unclear whether a better strategy could be used in this specific task. Besides the above mechanical considerations, wearing the exoskeleton certainly added other constraints than only inertial effects. For instance, hyperstaticity and imperfect compensation of frictions are present during HEI, which may widely disturb human motion. For example, wearing the exoskeleton likely increases friction in the dynamics of the human limb through interaction torque. This could actually improve the prediction of our model which simulated movements that were slightly too fast when moving with ABLE. At last, the psychological impact and the acceptability of wearing an exoskeleton have not been evaluated while they could constitute important factors beyond mechanistic considerations [28].

To conclude, wearing ABLE in transparent mode has a non-negligible but expectable impact on human movement. Well-known motor control principles persisted when wearing ABLE despite the complexity of the interaction but overall energy expenditure tended to increase with ABLE. This latter point is of course tempered by the fact than, when carrying heavy loads, the energy gain coming from load compensation provided by the robot will surpass that nominal smaller energy loss. Future studies will thus explore human-exoskeleton symbiosis along similar lines in tasks where carrying a load is desired.

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