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Grip force regulation when lifting an object with a robotic exoskeleton

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1. Introduction

Under normal conditions, anticipatory control enables a person to adjust grip forces according to their intended movement dynamics (Hermsdörfer et al, 2007). This capacity serves to maintain dexterous control and promote grip force economy while limiting the risk of dropping a handheld object during its displacement. When using a robotic exoskeleton, however, the user's intended movement dynamics may be either assisted, or corrected according to the control algorithm which is applied. The consequences of human-exoskeleton interaction may thus be observed through changes in hand trajectory, intersegmental coordination or muscular effort required to perform the gesture (McFarland and Fischer 2019). Exactly how these changes influence a person's ability to effectively regulate grip forces during object handling though, remains to be determined. In the present study, we measure grip force regulation during interactions with a robotic exoskeleton. Performance during a vertical lifting task was examined using transparent control, gravitational support, and a viscous force field. Our hypothesis was that interaction dynamics between the upper limb and the exoskeleton would result in increased grip forces for gravitational support and the viscous force field.

2. Methods

2.1 Participants

Thirty right-handed participants with an average age of 28 years and no neurological or orthopedic conditions were recruited to this study.

2.2 Exoskeleton and robotic control

An ABLE exoskeleton (Haption, Soulgé-sur-Ouette, France) with 4 degrees of freedom was used in this experiment. This device comprised 3 rotational axes at the shoulder (flexion/extension, abduction/adduction, internal/external rotation) and 1 at the elbow (flexion/extension). Three control algorithms were compared using this exoskeleton. (1) Transparent control (Tr), which used feedforward gravity compensation for the exoskeleton's weight, thus providing minimal resistance to voluntary movement. (2) Gravitational support (GS), which reduced the effect of gravity, such that the exoskeleton compensated for the equivalent of a 750 g mass at the level of the end effector. (3) Viscous force field (VF), which applied resistive forces proportional to the velocity at each rotational axis. Both GS and VF modes were adjusted to promote comanipulation without removing the need for user contribution in vertical movement (GS mode), or excessively constraining user action (VF mode). See Dubois et al. (2024) for specific configuration of control algorithms.

2.3 Experimental task

Each participant was randomly allocated to one of the three groups (Tr, GS, VF). The experimental task involved vertical lifting actions performed with the exoskeleton. While seated at a table, participants grasped an object from a table before placing it on a platform at a height of 30 cm. Each participant performed the vertical lifting action 30 times using only one robotic control algorithm.

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2.4 Data acquisition and statistical analysis

Grip force and object kinematics were recorded using an instrumented object composed of 6 load cells and an inertial measurement unit. The device measured 108 mm × 70mm × 40mm with a mass of 0.37 kg. Hand position was recorded using reflective markers (OptiTrack, Corvallis, USA). Load force parameters were calculated based on object mass and overall acceleration (i.e. combination of gravity and kinematic acceleration, per Hermsdörfer et al, 2007). Grip force control was then analyzed during the grasp (i.e. from contact to lift) and transport phases (i.e. from lift to place). Statistical analysis was performed with generalized linear mixed models (GLMM) using mode (Tr, GS, VF) as a fixed factor and participant intercepts as random effects. Tr mode served as the reference (i.e. control condition), with post-hoc testing used for direct comparisons between GS and VF modes.

3. Results and discussion

Grip force at lift was greater in GS mode compared to the Tr ($p < .001$) and VF ($p < .001$) modes. Maximum grip force during lifting was greater for the GS mode than for the Tr ($p < .001$) and VF modes ($p = .013$). Peak force ratio (i.e. maximum grip force divided by maximum load force) was also greater in GS mode than in the Tr ($p < .001$) and VF ($p = 0.04$) modes. One possible explanation for the increased grip force in the GS mode is that arm weight support may result in the actor perceiving an object held at the level of the hand as heavier. Alternatively, the potential uncertainty of movement dynamics during comanipulation with the GS mode may degrade the actor's capacity for anticipatory grip force control. Increased grip force during lifting might thus be a response to provide a greater safety margin to ensure object stability during displacement (c.f. Hermsdörfer et al, 2007).

No significant difference was observed for the peak velocity of the hand or the duration of the transport phase. At the same time, a greater variability in phase duration (as indicated by standard deviation) for interaction with GS and VF modes is suggestive of deficits in the planning and execution of end-effector kinematics during comanipulation (c.f. Sarlegna & Sainburg, 2009).

4. Conclusions

This study examined grip force regulation during a vertical lifting task with an upper limb exoskeleton. Our findings showed that participants using the GS mode applied excessive grip forces with respect to the load of the handheld object. This overcompensation may be indicative of challenges involved when anticipating movement dynamics during human-exoskeleton interactions with the GS mode. Reduced grip force efficiency may further imply limitations in dexterous abilities when using gravitational support during workplace activities or in the context of upper limb rehabilitation.

Table 1. Mean values for grip force parameters and temporal dynamics with different control algorithms.

Mode	Tr	GS	VF
Grasp phase duration	0.15 s (±0.05 s)	0.16 s (±0.06 s)	0.17 s (±0.12 s)
Maximum grip force	8.1 N (±2.4 N)	**11.3 N*** (±2.9 N)	8.8 N (±2.3 N)
Peak force ratio	2.1 (±0.7)	**2.8*** (±0.7)	2.5 (±0.7)
Peak hand velocity	0.23 $m \cdot s^{-1}$ (±0.10 $m \cdot s^{-1}$)	0.27 $m \cdot s^{-1}$ (±0.11 $m \cdot s^{-1}$)	0.25 $m \cdot s^{-1}$ (±0.08 $m \cdot s^{1}$)
Transport phase duration	1.08 s (±0.20 s)	1.09 s (±0.29 s)	1.22 s (±0.43 s)

Values in brackets represent standard deviation.

* Indicates GS > Tr and VF with p<0.05.

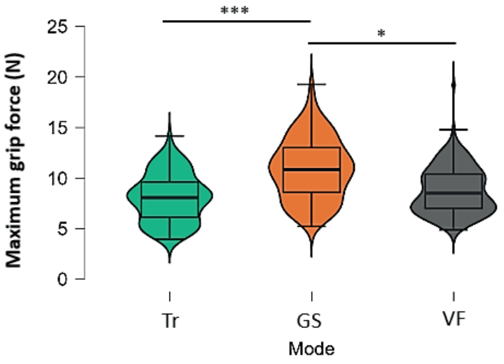

Figure 1. Maximum grip force for each control algorithm (*** = p<0.001; * = p<0.05).

Conflict of Interest Statement

The authors report no conflict of interest.

Contributor Roles

R.P., D.A, N.J. O.D and A.R.-B. conceived the experimental design. D.A. carried out data collection with the supervision of R.P, O.D and N.J. D.A. and R.P. performed formal data analysis and drafted the manuscript. Project administration and funding acquisition by R.P., N.J., G.d.M. and G.A. All authors participated in revision of the manuscript and agreed to the final version.

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