Equilibrium-point control for soft pneumatic-based wearable robots with joint antagonism

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I. Introduction

Wearable robots are envisioned to amplify the independence of people with movement impairments by providing daily physical assistance. For devices to be portable, comfortable, and safe, soft pneumatic-based robots are emerging as a potential solution. However, due to inherent complexities, including compliance and nonlinear mechanical behavior, feedback control for facilitating physical human-robot interaction remains a challenge. Here we summarize our recent work on a bio-inspired equilibrium-point control scheme for wearable robots that leverage antagonistic soft pneumatic actuators for physical interaction [1]. Our method integrates proprioceptive and exteroceptive feedback directly with the on/off valve behavior of the soft pneumatic actuators. The proposed human-robot controller is directly inspired by the equilibrium-point hypothesis of motor control, which suggests that voluntary movements arise through shifts in the equilibrium state of the antagonistic muscle pair spanning a joint. We hypothesized that the proposed method would reduce the required effort during dynamic manipulation without affecting the error. To evaluate our proposed method, we recruited seven pediatric participants with movement disorders to perform two dynamic interaction tasks with a haptic manipulandum.

II. Methods

Our main idea, summarized in Fig. 1, is that the equilibrium-point hypothesis of motor control provides a framework for facilitating physical interaction with soft pneumatic actuators. The hypothesis posits that voluntary movement results from shifts in the equilibrium angle of a joint and a combination of the stretch reflex with the passive mechanical properties of the muscles provide restoring torques if the joint angle deviates from the equilibrium-point [2]. In this way, the equilibrium-point represents a point attractor which the stretch reflex drives the joint towards, and a sequence of such equilibria produce movement. The key benefits of harnessing equilibrium-point control for robots are the ability to independently control the equilibrium configuration and joint impedance (e.g., variable impedance behavior), and to do so in a simplified (parametric) manner. Control techniques inspired from the equilibrium-point

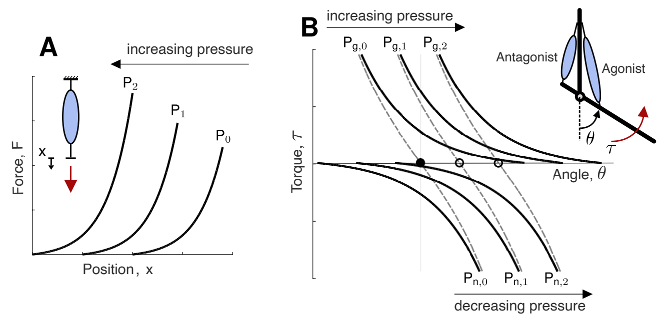

Fig. 1: Conceptual overview of the equilibrium-point hypothesis applied to soft pneumatic actuators. **A** Idealized force-deflection curves for three different nominal internal pressures of a contraction type soft actuator. Nominal pressure refers to the internal pressure *before* the external load is applied, which invariable changes the internal pressure do to volume changes. As the nominal pressure of the actuator is increased the force-deflection curve is shifted. **B** Idealized force-deflection curves for antagonistically configured contraction type soft pneumatic actuator for three different nominal internal pressures demonstrating a shift in equilibrium position of the joint while the net force-deflection curve is maintained constant. The depicted shift in equilibrium occurs by increasing the agonist actuator internal pressure ($P_{g,0} < P_{g,1} < P_{g,2}$) and decrease the antagonist actuator internal pressure ($P_{g,0} > P_{g,1} > P_{g,2}$).

hypothesis have been investigated previously for controlling antagonist soft actuators [3], [4], among other applications.

To leverage the equilibrium-point idea, we harness the *passive* properties of antagonistically arranged soft actuators to provide restoring torques if the joint angle deviates from a desired equilibrium-point rather than continuously regulating the internal pressure. When sufficient environment interaction (estimated via the internal pressure variations of the actuators) or movement intention (estimated via surface electromyography) is detected, a *reflex* is triggered which *shifts* the equilibrium point in the direction of interaction or intention, thereby provided assistive torques in that direction. Our central hypothesis is that the equilibrium-point controller will reduce the required effort to complete dynamic tracking tasks.

Seven children with clinically diagnosed cerebral palsy or an acquired static motor deficit between 8 and 22 years old (6 men, 1 women; mean = 15 years old; standard deviation = 4 years) were recruited from the Pediatric Movement Disorders Clinic at Children's Hospital of Los Angeles for this study, which was approved by the University of Southern Californias Institutional Review Board. The wearable robot used in the study is shown in Fig. 2 **A**, with details of actuator fabrication provided in Fig. 2 **B**, and an example inflation sequence of a single actuator shown in Fig. 2 **C**. The experimental setup is illustrated in Fig. 2 **D**, and consisted

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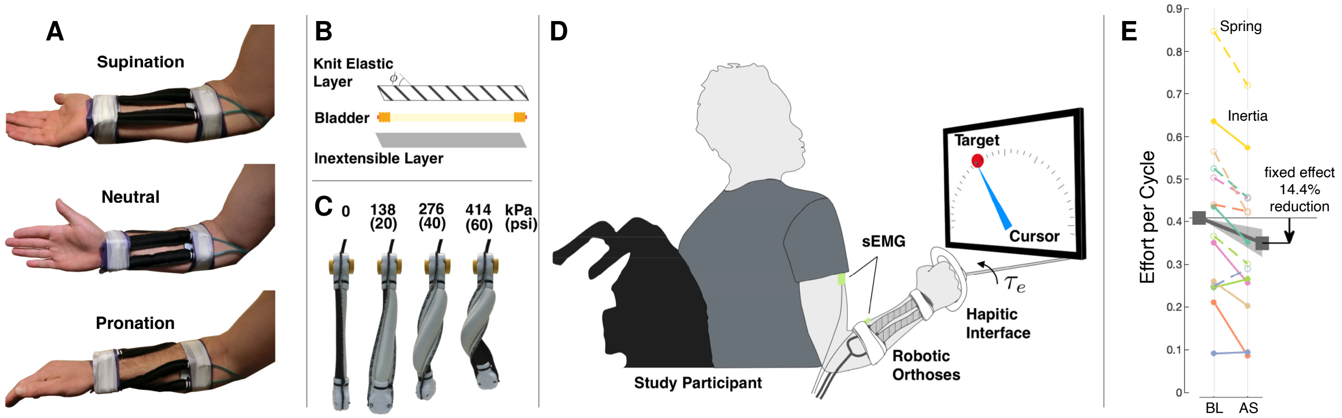

Fig. 2: Summary of the methods and main results from the study. **A** Medial view of the soft robotic orthosis during supination, neutral, and pronation configurations. Two antagonistic robotic orthosis elements are worn by the user on either side of the forearm. The element on dorsal side is configured to provide a pronating torque, while the element on the ventral side provides a supinating torque. Cohesive bandage (coban) and medical tape secure the human-robotic interface to the human user. **B** Actuator construction details. A knit elastic fabric layer (with knit angle ϕ) and an inextensible fabric layer are sewn together with a latex bladder enclosed. **C** Inflation sequence of a soft helical actuator. **D** An overview of the experimental setup, consisting of a participant with the soft wearable robot interacting with a one-degree-of-freedom rotational haptic interface. The total external torque τ_e depends on the haptic environment (either *Inertia-* or *Stiffness-Dominate*. For each trial, the goal is to track the moving target with the cursor, which is directly controlled by the haptic interface. A display provides the participant with visual feedback of the target (red circle) and cursor (blue pointer) positions. **E** Visual representation of the main results. Fixed and random effects from the linear mixed effects models for the *intercept* and *assist* independent variables. Fixed effects are denote with gray squares and trend line with the shaded region represents 95% confidence intervals. Random effects trend lines for each participant are denote with different colors and random effects for the dynamic (*Stiffness-* or *Inertia-Dominate*) are denoted with open and closed circles respectively.

of a participant physically interacting with a one-degree-of-freedom rotational haptic device with an adjacent computer screen displaying a desired sinusoidal tracking trajectory and the participant's current position. The haptic device rendered either a *Stiffness-Dominate* or *Inertia-Dominate* environment, which require different motor strategies.

III. Results

Here we summarize our main result from a linear mixed-effects model fit to the cycle level observations with the integral of participant effort during each cycle the outcome variable. The predictors included the interaction *power* during each cycle, the categorical *assistance* condition (e.g., either baseline (BS) or assist (AS)), and the *cycle number*, which captures learning effects over time. The random effects were the participant and the dynamic environment (*Stiffness-* or *Inertia-Dominate*). The model was chosen through a model selection process where candidate models were fit using the experimental data and evaluated based on the Bayesian information criterion (BIC). For the purpose of our hypothesis, the most important predictor is the categorical *assist*, which was found to have a coefficient of $\beta = -0.059$ (95% confidence intervals from -0.092 to -0.027 $p \approx$ 3.8e-4), supporting our hypothesis that the robot assistance will decrease user effort. The results show that the assistance from the wearable robot reduced effort in both haptic environments for all but two participants, and the fixed effect corresponds to a 14% decrease in effort (95% confidence interval from a 6.5% to a 22.4%), as shown in Fig. 2 **E**.

IV. Discussion

Here we proposed a novel equilibrium-point controller and tested it's ability to provide physical assistance to the forearm rotations of children with motor impairments. Through an experiment that consisted of trajectory tracking in different dynamics environments the wearable robot demonstrated the ability to be volitionally controlled by all the users, which was achieved through triggered shifts in the robot's equilibrium-position. We analyzed the data with a linear mixed-effects model with participant effort as the outcome. The results provide a strong indication that the wearable robot reduces user effort. In addition, the models provided insight into the other main factors effecting effort, including the participant specific capabilities and learning over time (see [1] for details). We envision several future advancement to the equilibrium-point control method, including the possibility of general impedance modulation capabilities. In summary, the equilibrium-point control method provides a new framework for facilitating human-robot interactions.

References

[1] J. Realmuto and T. Sanger, "Assisting forearm function in children with movement disorders via a soft wearable robot with equilibrium-point control," *Frontiers in Robotics and AI*, 2022 (in review).

[2] A. G. Feldman, "Once more on the equilibrium-point hypothesis (λ model) for motor control," *Journal of motor behavior*, vol. 18, no. 1, pp. 17–54, 1986.

[3] Y. Ariga, H. T. Pham, M. Uemura, H. Hirai, and F. Miyazaki, "Novel equilibrium-point control of agonist-antagonist system with pneumatic artificial muscles," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, 2012, pp. 1470–1475.

[4] Y. Ariga, D. Maeda, H. T. Pham, M. Uemura, H. Hirai, and F. Miyazaki, "Novel equilibrium-point control of agonist-antagonist system with pneumatic artificial muscles: Ii. application to emg-based human-machine interface for an elbow-joint system," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 4380–4385.