Soft robots that mimic the neuromusculoskeletal system

Manolo Garabini[1], Cosimo Della Santina[1], Matteo Bianchi[2],
Manuel Catalano[2], Giorgio Grioli[2], and Antonio Bicchi[1,2]

Abstract— **In motor control studies, the question on which parameters human beings and animals control through their nervous system has been extensively explored and discussed, and several hypotheses proposed. It is widely acknowledged that useful inputs in this problem could be provided by developing artificial replication of the neuromusculoskeletal system, to experiment different motor control hypothesis. In this paper we present such device, which reproduces many of the characteristics of an agonistic-antagonistic muscular pair acting on a joint.**

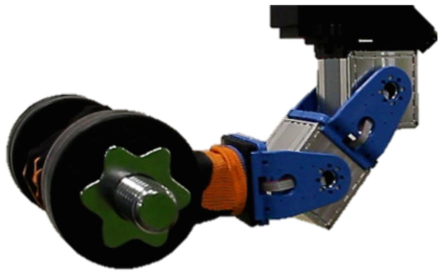


Fig. 1. A robotic arm build with Qbmove VSA actuators lifting a 5Kg weight.

I. INTRODUCTION

Qbmoves (see Fig. 1) are modular variable stiffness actuators (VSA), namely actuators that can physically change their mechanical stiffness (for an exhaustive review on the subject see [10]). The qbmoves have been designed to be modular, low cost, and plug-and-play [2]. Because of their modularity, these actuators can be interconnected to form, in short time, several robotic prototypes for different applications. They are based on the agonistic-antagonistic paradigm (see Fig. 2(b)). More specifically the output shaft is actuated by two prime movers via two elastic transmissions. Each transmission is composed of a spring with non-linear torque-deflection characteristic. Due to the ability of change their stiffness qbmoves and similar devices (see [1]) have already found applications in many robotic fields, showing improvements w.r.t. conventional actuators in the level safety in human-robot interaction and efficiency, to name a few.

In this work, we present the analogies between qbmoves and an agonistic-antagonistic muscular pair. We believe that this analogy can make such system an ideal platform for testing human motor control theories (as e.g. in [8] [9]), and to develop assistive robotic devices.

II. MUSCLE MODEL

In his seminal work [3], Feldman proposed the λ-model: the signals sent from the brain to muscles are assumed to set the threshold length λ of each muscle (which determines activation threshold of α-motoneurons). When λ is set for each muscle, a corresponding equilibrium position, which also depends on the external load, is achieved for the system. The main result underpinning the so-called Equilibrium Point Hypothesis (EP-H) is that motion can be generated by the central nervous system through a gradual transition of equilibrium points (see e.g. [5]), i.e. by a trajectory for $\lambda(t)$. Any muscle has at least an antagonistic one acting on the same joint. According to λ-model, a pair of variables can be used to describe the central regulation. These variables are defined as combinations of the two threshold lengths of each muscle. The first one, named *r-command*, corresponds to a shift of the joint compliant characteristic along the angle axis. The second one, named *c-command*, corresponds to a change in the slope of the joint compliant characteristic. As a consequence, in case of no external load, r causes joint movement/torque and c causes joint stiffness changes [4].

In [6], authors approximate the resulting muscle force using an exponential function of the form, $f = \rho(e^{\delta A} - 1)$, where ρ is a magnitude parameter related to force-generating capability and it is specific for each muscle, δ is a form parameter and it is the same for all muscles. A is the muscle activation and depends on the difference between the current length l and the threshold length $\lambda(t)$ and the rate of change of muscle length $\dot{l}$ through a parameter $\mu(t)$. Moreover, a reflex delay d can be observed in the unloading response of human arm muscles (see [6]). Thus

$$A(t) = [l(t-d) - \lambda(t) + \mu(t)\dot{l}(t-d)]^+ \quad (1)$$

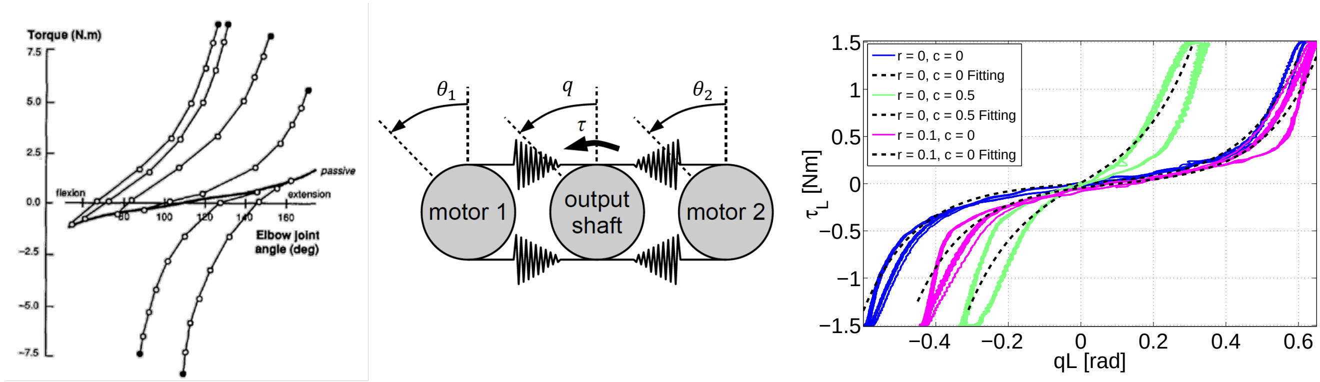
where $[x]^+$ is 0 when $x \leq 0$, and x otherwise. If a couple of agonist-antagonist muscles act on the same joint, the equilibrium of the corresponding mechanical system is such that $\tau + R(f_1 + f_2) = 0$, where τ represents the external load, and R is the instantaneous lever arm. Assuming the same value ρ for each muscle and naming q as the forearm angular position w.r.t. the arm (and hence $\ell = Rq$), forces f_1 and f_2 are given by

$$\begin{aligned} f_1 = &\ \rho(e^{\delta A_1} - 1), \quad f_2 = -\rho(e^{\delta A_2} - 1) \\ A_1 = &\ Rq(t-d) - \lambda_1(t) + \mu(t)R\dot{q}(t-d) \\ A_2 = &-Rq(t-d) + \lambda_2(t) - \mu(t)R\dot{q}(t-d)\,. \end{aligned} \quad (2)$$

Given $\tau = 0$, $\dot{q} = 0$ and $d = 0$, the equilibrium position can be obtained in terms of λ_1 and λ_2 solving $e^{\gamma(R\bar{q}-\lambda_1)} - e^{\gamma(-R\bar{q}+\lambda_2)} = 0$ for $\bar{q} = \frac{r}{R}$, where $r := \frac{\lambda_1+\lambda_2}{2}$. The stiffness σ can be evaluated in the equilibrium position as a function of λ_1 and λ_2 by computing the derivative of the external torque w.r.t. the link position $\sigma = \frac{\partial\tau}{\partial q}\Big|_{q=\bar{q}} = 2\rho\delta R^2 e^{\delta c}$, where $c := \frac{\lambda_1-\lambda_2}{2}$.

[1]"Enrico Piaggio", University of Pisa, Largo Lucio Lazzarino 1, 56126 Pisa, Italy cosimodellasantina@gmail.com

[2]Department of Advanced Robotics, Istituto Italiano di Tecnologia, via Morego, 30, 16163 Genova, Italy



(a) (b) (c)

Fig. 2. Experimentally measured force–length characteristics in robotic and natural system. In (a) is presented the elastic characteristic of agonist and antagonist muscles acting on the elbow joint in the human, taken from [6]. In (b) it is presented the robot agonist-antagonistic mechanism, with major quantities underlined. In (c) is presented the qbmove characteristic for different values of equilibrium point r and stiffness c. Under each experimental characteristic is reported the one resulting from the fitting of Eq. (4). As in the human muscle, a change in *r-command* corresponds to a shift of the joint compliant characteristic along the angle axis, and a change in *c-command* corresponds to a change in the slope of the joint compliant characteristic.

III. A Robotic Counterpart

Let us now consider the qbmove actuator, in Fig. 1. The force-length characteristic of the nonlinear spring between the link and the actuator is

$$\tau_i = \alpha(e^{\beta(q-\theta_i+\eta\dot{q})} - 1) \quad (3)$$

where α, β and η are parameters that determine the shape of the force-length characteristic and θ_i is the position of the motor acting on the link throughout the nonlinear spring. Fig. 2(c) shows three different force-length characteristics obtained by experimentations and their approximations (black line) given by (3), setting all parameters therein. The equilibrium position of this type of VSA is such that $\tau + \tau_1 + \tau_2 = 0$, where τ represents the external load (see figure 2(b)). τ_1 and τ_2 are the torques that each motor applies to the link, given by

$$\tau_1 = \alpha e^{\beta(q-\theta_1)} - \mu, \quad \tau_2 = -\alpha e^{\beta(-q+\theta_2)} + \mu\,. \quad (4)$$

The equilibrium position $\bar{q}$ of the VSA can be determined by imposing $\tau = 0$ and $\dot{q} = 0$, obtaining $0 = \tau_1 + \tau_{m,2} = \alpha e^{\beta(\bar{q}-\theta_1)} - \alpha e^{\beta(-\bar{q}+\theta_2)}$, which implies

$$\bar{q} = \frac{\theta_1 + \theta_2}{2} = q_\ell \quad (5)$$

The stiffness σ can be obtained as a function of $\theta_{m,1}$ and $\theta_{m,2}$ by determining the derivative of the external torque w.r.t. the link position q and evaluating it in $\bar{q}$, i.e.

$$\sigma = \left.\frac{\partial\tau}{\partial q}\right|_{q=\bar{q}} = 2\alpha\beta e^{\beta k}, \quad (6)$$

where $k = \frac{\theta_2-\theta_1}{2}$. For details related to the technical characteristics of Qbmove actuators please refer to [7].

IV. Conclusions

Concluding, for both muscles and agonistic-antagonistic VSAs, the stiffness σ can be described by a function of type $\sigma = Ae^{\gamma S}$. Furthermore, the equilibrium position is $\bar{q} = \frac{\lambda_1+\lambda_2}{2R(t)} = \frac{r}{R(t)}$ for muscles and $\bar{q} = \frac{\theta_{m,1}+\theta_{m,2}}{2} = q_\ell$ for VSAs. The role of λ_i in the EP-H has hence a robotic counterpart that, in our framework, is represented by motor positions $\theta_{m,i}$.

Parameters	Muscle	VSA
A	$2\rho\delta R^2(t)$	$2\alpha\beta$
γ	δ	β
S	$c = \frac{\lambda_2-\lambda_1}{2R(t)}$	$k = \frac{\theta_{m,2}-\theta_{m,1}}{2}$

The presented similarities between qbmove and muscular system could be profitably employed to develop a robotic testbed for experimenting motor control hypothesis. Moreover a positive side effect can be the development of novel control paradigms inspired by the motor control theory. Future works will be devoted to advance in this directions.

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