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The NEURARM bio-inspired antagonistic joint: preliminary results on the Equilibrium Point Hypothesis position and stiffness control

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SCIENTIFIC BACKGROUND

The human arm is a notable mechanical mechanism for its ability to perform a great variety of tasks. Although slower, weaker and less accurate than high-performance robots of today, the human arm is without equal in terms of versatility, robustness and gracefulness. The key characteristic of these last properties may be attributed to the mechanical properties of the muscle themselves and the strategy used to control them. A pair of muscles powering the human joint in antagonistic configuration provides the peculiar characteristics of the so-called 'equilibrium point hypotheses' for human motor control [1,2,3]. Since muscles have a natural stiffness and viscosity that varies with the muscle activation level, the Central Nervous System (CNS) can generate stable equilibrium postures, towards which the arm is attracted, by properly regulating the activation levels of antagonistic muscles. Moreover, the CNS can generate stable posture and even movements in absence of sensory feedback, by shifting the equilibrium point [4]. By co-activating antagonistic muscles in parallel, the mechanical impedance (i.e. stiffness) can also be regulated.

The NEURARM Platform: a robotic model of the human arm

Table 1: Human arm vs. the NEURARM functional features

HUMAN ARM	NEURARM
Muscles (non-linear actuators)	Hydraulic pistons working with non-linear springs connected on the cable
Agonist-antagonist tendon driven	Agonist-antagonist driving cables
Tendons fixed on the bones	Two configurations: 1) cables fixed on the joint (shoulder) 2) cables fixed on the link (forearm)
Tunable contraction force	Electro valves and pressure sensors
Muscle spindles (stretching sensors)	Linear potentiometers on the pistons
Joint receptors (angle sensors)	Angle sensors on the joints
Golgi tendon organs (tension sensors on the tendons)	Load cells on the cables

The NEURAM Platform (Fig. 1) is a functionally bio-inspired robotic arm developed to:

- ❑ investigate neuroscientific hypotheses on human motion control strategies, like the 'equilibrium point hypothesis';
- ❑ test new bio-inspired control strategies for robotic artefacts closely interacting with humans for rehabilitation and assistive purposes (i.e. prostheses, active orthoses, wearable exoskeletons).

The NEURARM Platform [5] is a 2 link–2 degrees of freedom (DoF) planar robotic arm that mimics the main functional futures of the human upper limb (Tab. 1).

The NEURARM has its link masses and inertia similar to those of the European standard man and it is powered by a remote hydraulic actuation. Each NEURARM joint is actuated by two driving tendon cables acting on a pulley in an antagonistic configuration.

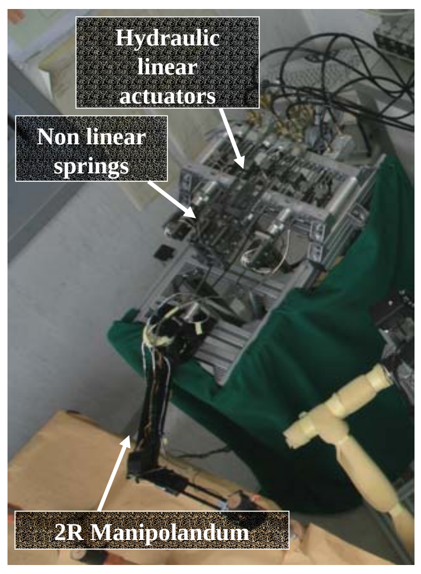


Fig. 1: The NEURARM Platform

The non linear elastic element

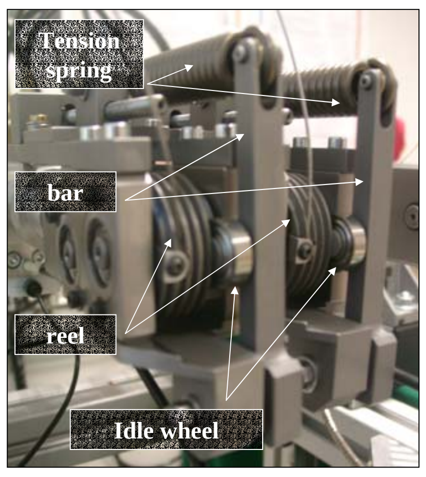


Fig. 2: The non-linear elastic element

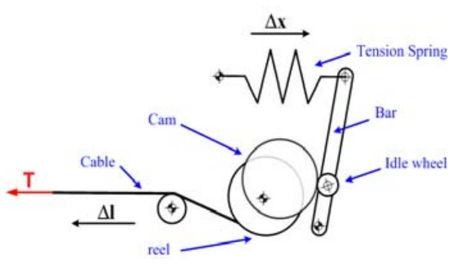


Fig. 3: Working principle of the non-linear elastic element

The non-linear elastic element (Fig. 2) is a critical component in the NEURARM transmission for the joint stiffness regulation. It has been designed to mimic the static non linear force-elongation characteristic of the human muscle-tendon complex [6,7] and to obtain a resulting joint stiffness range comparable to that of the human elbow and shoulder [8].

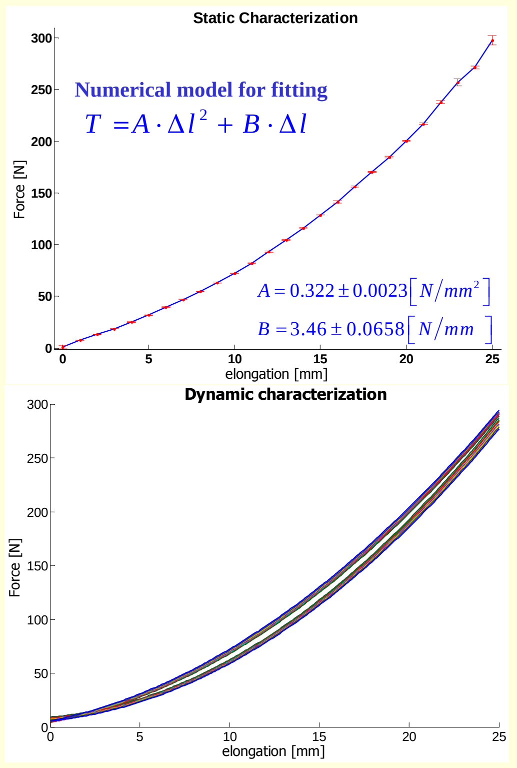
The non-linear elastic element obtains the desired force-elongation curve thanks to the combined action of (Fig. 3):

- ❑ a kinematics function: non linear relationship between the displacement of the cable (Δl) and the elongation of the spring (Δx);
- ❑ a force transformation function: the spring force is transmitted to the cable in a non linear manner, thanks to a cam mechanism.

In detail, the working principle of the mechanism is described in 5 steps:

- ❑ the steel cable is wrapped around a reel, which is fixed with a cam;
- ❑ the cam transmits the force and the movement to a bar, by means of an idle wheel, used to minimize the friction;
- ❑ the bar is hinged down on the frame, and on its opposite extremity is connected to the tension spring, that is fixed to the frame;
- ❑ a displacement (Δl) of the cable rotates the reel and therefore the cam;
- ❑ the cam moves the bar through the idle wheel, and so the spring is stretched.

The non-linear elastic element force vs. elongation behaviour has been characterized both in static and dynamics conditions. The static analysis points out that for an antagonist joint, whose pulley radius is 0.03 m, the theoretical stiffness range, as described in [9], is 6.22-35.1 Nm/rad, comparable to that of the human shoulder and elbow moving. It is possible to customize and increase this interval simply changing the tension spring in the non linear element mechanism with a stiffer ones. The dynamic analysis shows that the non-linear elastic behavior is little affected by velocities: the maximum hysteresis was of 18.34 N, which corresponds approximately to 6% of the force at maximum elongation. The force-elongation characteristic is anyway well approximated by the static numerical model.



The static curve was obtained by displacing the cable extremity, from the resting position (cable force about equal to 0 N), up to 25 mm (with 1 mm step) and recording the cable force at steady state. The static characterization was repeated 10 times for statistical purposes.

The dynamic characterization was obtained by performing 5 loading-unloading cycles for 8 different elongation velocities in the range 10-400 mm/min (elongation range equal to 0-25 mm).

The bio-inspired variable stiffness antagonist joint

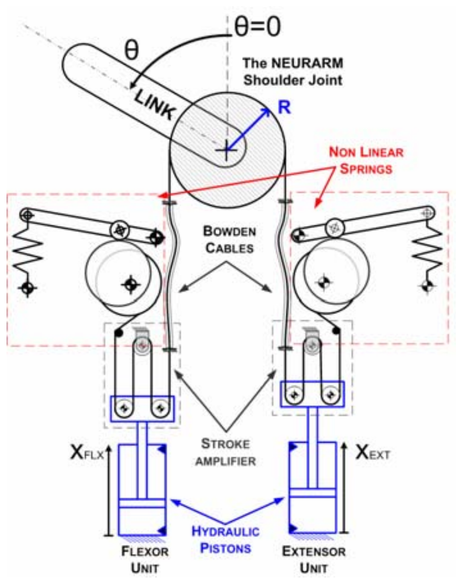


Fig. 4: The NEURARM shoulder joint actuation scheme

Two non-linear elastic elements were preliminarily integrated on the shoulder joint of the NEURAM platform. The joint actuation scheme (see Fig. 4) is based on two driving tendon cables acting on a pulley, by means of Bowden-cables, in an antagonistic configuration. Each driving cable is powered by a contractile element (hydraulic piston) in series with a non-linear elastic element and a four-times piston stroke amplifier.

The open loop controller is based on a two levels hierarchical architecture, as illustrated in Fig. 5. The **high level controller** converts the desired joint position Θ_{des} and stiffness level K_{des} in the two hydraulic piston desired positions $X_{FLX,des}$ and $X_{EXT,des}$.

The joint stiffness is regulated by an equal deformation of the antagonistic non-linear springs (that mimics the antagonistic muscles co-activation), as resulting from a common variation X_{COM} of the piston positions X_{FLX} and X_{EXT}.

The joint position is regulated by displacing the hydraulic pistons of the same quantity but in opposite directions (that mimics the shift of the joint equilibrium position as resulting from a differential antagonistic muscles activation), i.e. to increase Θ it is need to decrease X_{FLX} and increase X_{EXT}. The **low level controller** is a closed loop position controller that permits the tracking of the desired piston positions $X_{FLX,des}$ and $X_{EXT,des}$ [9]. Instantaneously, the positions X_{FLX} and X_{EXT} determine the joint equilibrium angle Θ_{eq}. The open loop controller was characterized both in static and dynamic conditions.

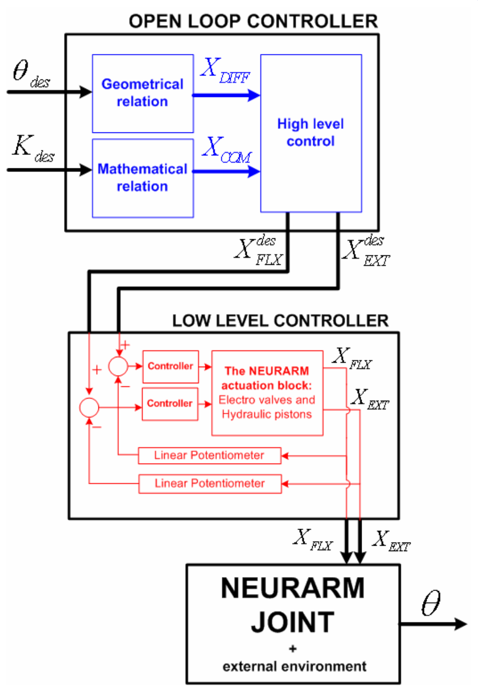
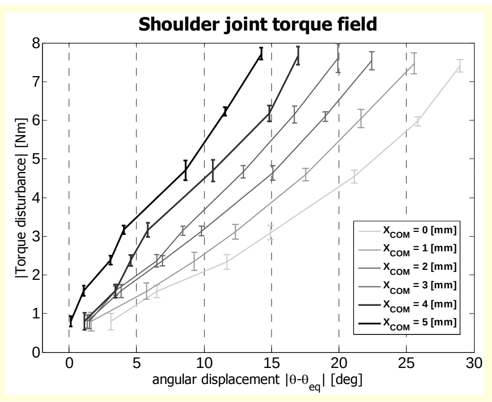


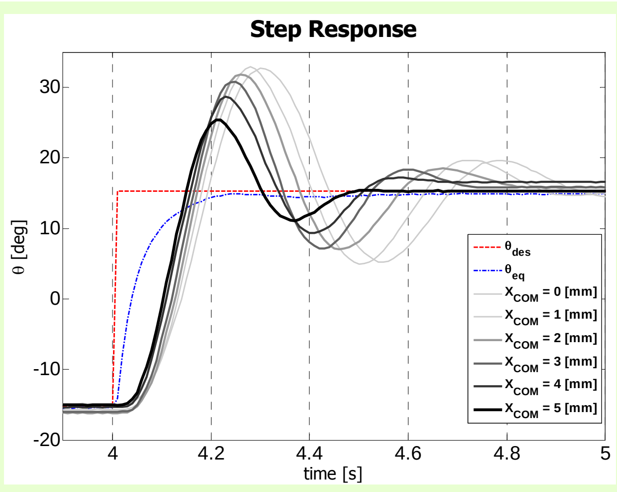
Fig. 5: The open loop EPH based position and stiffness control



The static characterization was aimed to qualitatively investigate that increasing values of X_{COM}, corresponding to a theoretical gradual increasing of the joint stiffness, determine variable convergent torque fields at the NEURARM joint.

For a fixed equilibrium joint angle Θ_{eq} increasing torque distubances were applied by an ad hoc set up [10].

The results show that as X_{COM} increases the NEURARM joint has an effective increase of the stiffness.



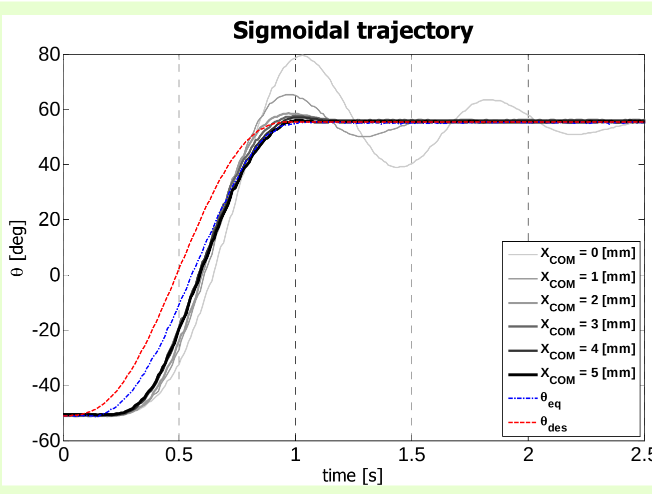


Table 2: Dynamics identification

X_{COM} [mm]	f_0 [Hz]	ζ	RMSE [deg]
0	2.06	0.181	2.16
1	2.26	0.190	1.86
2	2.51	0.203	1.89
3	2.77	0.210	1.78
4	2.95	0.224	1.81
5	3.34	0.265	1.52

The different dynamic behavior of the joint at different stiffness levels was evaluated by a 30 deg step response. The NEURARM joint was modeled as a second order underdamped system, and the data collected were used to identify the transfer function $G(s) = \Theta(s)/\Theta_{eq}(s)$ (Matlab® Identification Toolbox). The identification results showed that for the same desired trajectory $\Theta_{des}(t)$, the increasing of the stiffness causes both the characteristic frequency f_0 and the damping factor ζ of the system increase (Tab. 2). While an increasing f_0 determines a faster joint dynamic response, the increasing ζ causes the overshoot lowering [10].

The open loop controller was tested to perform a bell shaped velocity profile fast movement (peak velocity ~250 deg/s) too. Coherently, the stiffness increasing determines a reduction of the overshoot and a faster response. High values of stiffness makes the joint able to perform fast trajectories without overshoot even in open loop fashion, that is really human like [4].

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