1. Rationale

A pair of muscles powering the human joint in an antagonistic configuration exemplifies the main difference between standard industrial robots and biological motor systems. Since muscles have a natural stiffness that varies with the muscle activation level, the central nervous system can generate stable equilibrium postures, towards which the arm is attracted, by properly regulating the activation levels of antagonistic muscles [1]. The elastic properties of muscles contribute to the finite stiffness/compliance properties of the limb, to the stability of the neuro-musculo-skeletal system in the face of significant feedback delays and even allow for the generation of target movements in absence of sensory feedback, by shifting the equilibrium point [2]. Control theories based on the presence of the EP in biological motor systems [3] suggest that movements are programmed as a shift of equilibrium positions rather than through an explicit computation of forces. Thus, there is no need to solve the “inverse dynamics problem” for calculating the torque required to move the arm on the desired trajectory.

The implementation of a given neuroscientific hypothesis on a real mechanical system could provide a tool under the full control of the experimenter, reproducing the main functional features of the human arm and being able to interact with the same physical environment of the human. To this end we developed the NEURARM platform, a bio-mimetic planar robotic arm reproducing key features of the human arm as identified at the level of joints and muscles. In particular:

1. the kinematic parameters and inertia are similar to that of the human being;
2. the actuation mimics the main physical features of the human actuator system, such as:
   a. the use of tendons to transfer force;
   b. passive elasticity of muscles in absence of any neural feedback;
   c. implementation of antagonistic pairs of muscles;
   d. non-linearity of the elastic behavior allowing modulation of net stiffness through co-activation of opposing muscles.

These criteria relate to the constituent components of the human described at the level of the joints and mechanical linkages. If these criteria are met, the more global features of the dynamical system, such as the endpoint impedance and the movements induced by a motor command, should emerge. If, indeed, this goal is reached, one can use the thus-designed robotics system to test hypotheses about human motor control, allowing one to distinguish between the
dynamical properties of the skeletal elements and actuators that contribute to the control of the limb from the active neural processes that the CNS uses to produce movements.

2. Robotics Implementation

The NEURARM antagonistic actuation system in combination with the “muscle-like” actuators, which have a non-linear force/elongation characteristic, can generate a convergent torque field around an equilibrium position of the joint. Once the equilibrium position is set, the torque field is generated and maintained by the intrinsic properties of the actuation system. The controller is also able to modify the mechanical behavior of the joint by acting on the slope of the torque field (see Figure 1a).

According to the principles of impedance control, the elastic properties of the neuromuscular system are important not only for posture maintenance but also to generate movements. The NEURARM actuation was designed to allow the joint stiffness regulation to be independent of the position control, as shown in Figure 1b. In addition by regulating the joint impedance NEURARM can modify its end-point elastic behavior. Figure 1c shows how the stiffness ellipses is affected by a displacement of the joint positions while the joint stiffness level is kept constant, whereas Figure 1d illustrates the effect of the joint stiffness levels adjustment in a fixed position.

The experimental results pointed out that the NEURARM performance is sufficiently close to those of the human arm for certain key features, both in static and dynamic conditions. Therefore, the NEURARM proves to be a suitable robotic model of the human arm and, as such, it could represent a possible innovative and powerful tool for neuroscience investigation.

[4].

Acknowledgements

This work was partly supported by the EU within the EVRYON Collaborative Project STREP (Evolving Morphologies for Human-Robot Symbiotic Interaction, FET Proactive Project FP7-ICT-2007-3-231451).

References