

Paper:

# Kinematic Robustness of Manipulating Systems

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Present day mechanical manipulators have poor performances when compared with the human arm. In fact, joint-driven manipulators are not efficient due to the high actuator requirements imposed by the transients of the operational tasks. Muscle-actuated arms are superior because the anatomic levers adapt the manipulating exigencies to the driving linear actuators. The kinematic analysis of these systems highlights its main properties and constitutes a step towards the design of new mechanical biological-like robotic structures adopting linear actuators replacing the standard rotational joint-driving motor systems.

**Keywords:** robotics, manipulators, biomechanics, kinematics

## 1. Introduction

The low performances of robotic manipulators, when compared with the human arm, motivated the development of new mechanical structures. Research in this area lead to the development of mathematical and computer models of the kinematic and dynamic phenomena<sup>1-7</sup>. Nevertheless, clear guidelines towards the implementation of optimal manipulating structures are still lacking. Joint-driven manipulators, with standard actuators, are not well adapted to the transients imposed by the robotic applications<sup>8-9</sup>. Alternative structures having muscle-like actuators and appropriate mechanical levers<sup>10-15</sup>, may allow more efficient manipulating structures.

This paper investigates the arm biomechanics and evaluates its influence upon the driving actuators. In this perspective the article is organized as follows. Section two formulates a geometrical model of the human arm and section three analyzes the performances of muscle-actuated manipulators. Motivated by the results, section four studies the development and control of linear actuators. Finally, section five outlines the main conclusions.

## 2. Geometric Model of the Human Arm

Extensive studies<sup>16-25</sup> have been carried out on the

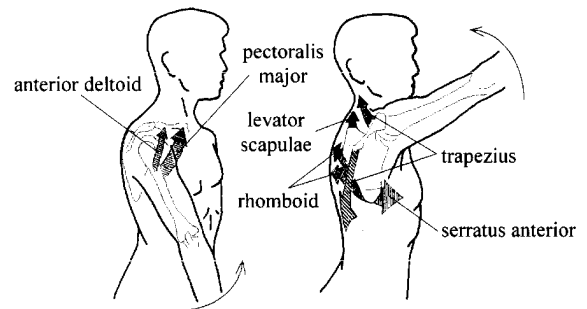


Fig. 1. Shoulder joint during flexion on sagittal plane.

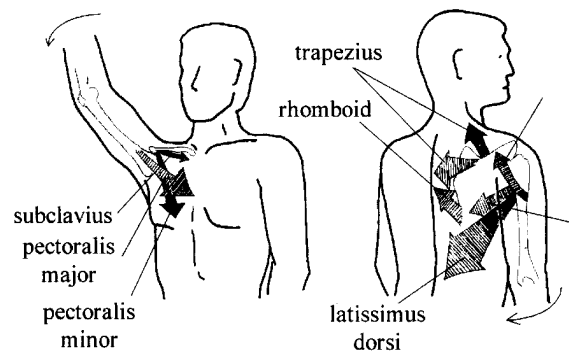


Fig. 2. Shoulder joint during extension on sagittal plane.

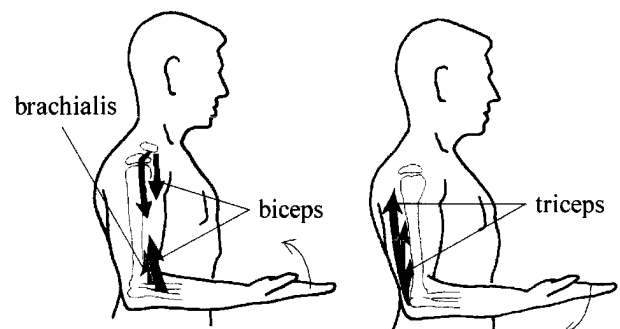


Fig. 3. Elbow joint during flexion and extension on sagittal plane.

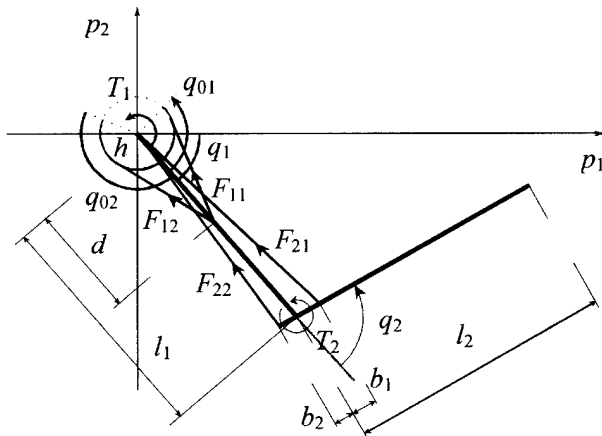


Fig. 4. Model of human arm on sagittal plane for shoulder and elbow.

analysis of the human arm, still there are not definite conclusions. Therefore, in order to simplify matters, only the arm motion in the sagittal plane is considered (Fig. 1-3).

A simple observation reveals that, at the biomechanical level, the human arm is driven by two main articulations: the shoulder and the elbow. Due to the fact that muscles are unidirectional actuators, articulations are driven by pairs of antagonist muscles activated alternatively during flexion and extension.

Figure 4 shows a simplified geometrical model of this mechanism in the sagittal plane<sup>26-27</sup>. The anterior and posterior deltoids drive the shoulder joint and have insertions both on the humerus and the pulley structure. Here, the pulley accounts for the scapulae, the clavicle, the sternum and the trunk, and has an independent motion ( $q_{01}$  for flexion and  $q_{02}$  for extension) of the arm movement ( $q_1$ ). In this sense, the relative position of the arm and the pulley is controlled by the pair of deltoids, while the absolute position of the pulley is controlled by muscles such as the serratus anterior, the trapezius and the rhomboids.

The elbow reveals a simpler structure. For the movement of the elbow in the sagittal plane ( $q_2$ ), the main muscles involved are the biceps brachii and the triceps brachii while, to a smaller significance, we can mention the brachialis and the anconeus.

In what concerns the relations between positions, velocities and accelerations on the operational and joint spaces (i.e.  $\{q, \dot{q}, \ddot{q}\}$  and  $\{p, \dot{p}, \ddot{p}\}$ , respectively), for the structure we have the conventional robot inverse kinematics:

$$\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} \tan^{-1}\left(\frac{p_2}{p_1}\right) - \tan^{-1}\left(\frac{l_2 S_2}{l_1 + l_2 C_2}\right) \\ \cos^{-1}\left(\frac{p_1^2 + p_2^2 - l_1^2 - l_2^2}{2l_1 l_2}\right) \end{bmatrix} \dots \dots \dots (1a)$$

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \frac{1}{hl_2 S_2} \begin{bmatrix} l_2 C_{12} & l_2 S_{12} \\ -l_1 C_1 - l_1 C_{12} - l_1 S_1 - l_2 S_{12} \end{bmatrix} \begin{bmatrix} \dot{p}_1 \\ \dot{p}_2 \end{bmatrix} \dots \dots \dots (1b)$$

$$\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} = \frac{1}{l_1 l_2 S_2} \begin{bmatrix} l_2 C_{12} & l_2 S_{12} \\ -l_1 C_1 - l_1 S_1 \end{bmatrix} \begin{bmatrix} \ddot{p}_1 \\ \ddot{p}_2 \end{bmatrix} + \frac{1}{l_1 l_2 S_2} \begin{bmatrix} l_1 l_2 C_2 & l_2^2 \\ -l_1^2 - l_1 l_2 C_2 \end{bmatrix} \begin{bmatrix} \dot{q}_1^2 \\ \dot{q}_2^2 \end{bmatrix} \dots \dots \dots (1c)$$

Nevertheless, for the muscle-driven structure depicted in Fig.1 we have a further kinematic transformation between the joint space and the actuator space  $\{z, \dot{z}, \ddot{z}\}$ .

For the shoulder articulation we can derive the expressions of the actuators range of motion, displacements ( $z_{1i}$ ), velocities ( $\dot{z}_{1i}$ ) and accelerations ( $\ddot{z}_{1i}$ ) both for the anterior ( $i=1$ ) and the posterior ( $i=2$ ) deltoids. In this case, the relationship between  $q_1$  and  $q_{01}$  or  $q_{02}$  obeys a kinematic control scheme according with the equations:

$$q_{01} = \begin{cases} 0.528\pi - 0.5q_1 & -2\pi/3 \leq q_1 < -\pi/2 \\ 0.278\pi - q_1 & -\pi/2 \leq q_1 \leq -\pi/6 \\ 0.361\pi - 0.5q_1 & -\pi/6 \leq q_1 < \pi/6 \\ 0.411\pi - 0.8q_1 & \pi/6 \leq q_1 \leq 4\pi/9 \end{cases} \dots (2a)$$

$$q_{02} = \begin{cases} 1.083\pi - 0.5q_1 & -2\pi/3 \leq q_1 < -\pi/2 \\ 0.833\pi - q_1 & -\pi/2 \leq q_1 < -\pi/6 \\ 0.917\pi - 0.5q_1 & -\pi/6 \leq q_1 \leq \pi/6 \\ 0.75\pi + 0.5q_1 & \pi/6 \leq q_1 \leq 4\pi/9 \end{cases} \dots (2b)$$

These expressions represent a compromise for the minimization of the requirements posed to the pulley and arm actuators, respectively. Moreover, for the flexion and extension there are different situations for the interaction of the pulley and the muscles. For the flexion we have two distinct cases ( $h$  and  $d$  are geometrical parameters):

- For  $-2\frac{\pi}{3} \leq q_1 < -\frac{\pi}{18}$  the anterior deltoid is wound around the pulley, yielding:

$$z_{11} = h [q_{01} - \sin^{-1}(\sqrt{d^2 - h^2}/d)] + \sqrt{d^2 - h^2} \dots (3a)$$

$$\dot{z}_{11} = h\dot{q}_{01} \dots \dots \dots (3b)$$

$$\ddot{z}_{11} = h\ddot{q}_{01} \dots \dots \dots (3c)$$

- For  $-\pi/18 \leq q_1 \leq 4\pi/9$  the anterior deltoid is acting freely (i.e. is not wound around the pulley) leading to:

$$z_{11} = \sqrt{d^2 + h^2 - 2dhC_{01}} \dots \dots \dots (4a)$$

$$\dot{z}_{11} = (dhS_{01}/z_{11})\dot{q}_{01} \dots \dots \dots (4b)$$

$$\ddot{z}_{11} = \frac{dh}{z_{11}} \left[ \left( \frac{z_{11}^2 C_{01} - dhS_{01}^2}{z_{11}^2} \right) \dot{q}_{01}^2 + S_{01} \ddot{q}_{01} \right] \dots \dots \dots (4c)$$

For the extension we have a single case where the posterior deltoid is wound around the pulley through the total range of motion  $-2\pi/3 \leq q_1 \leq 4\pi/9$  :

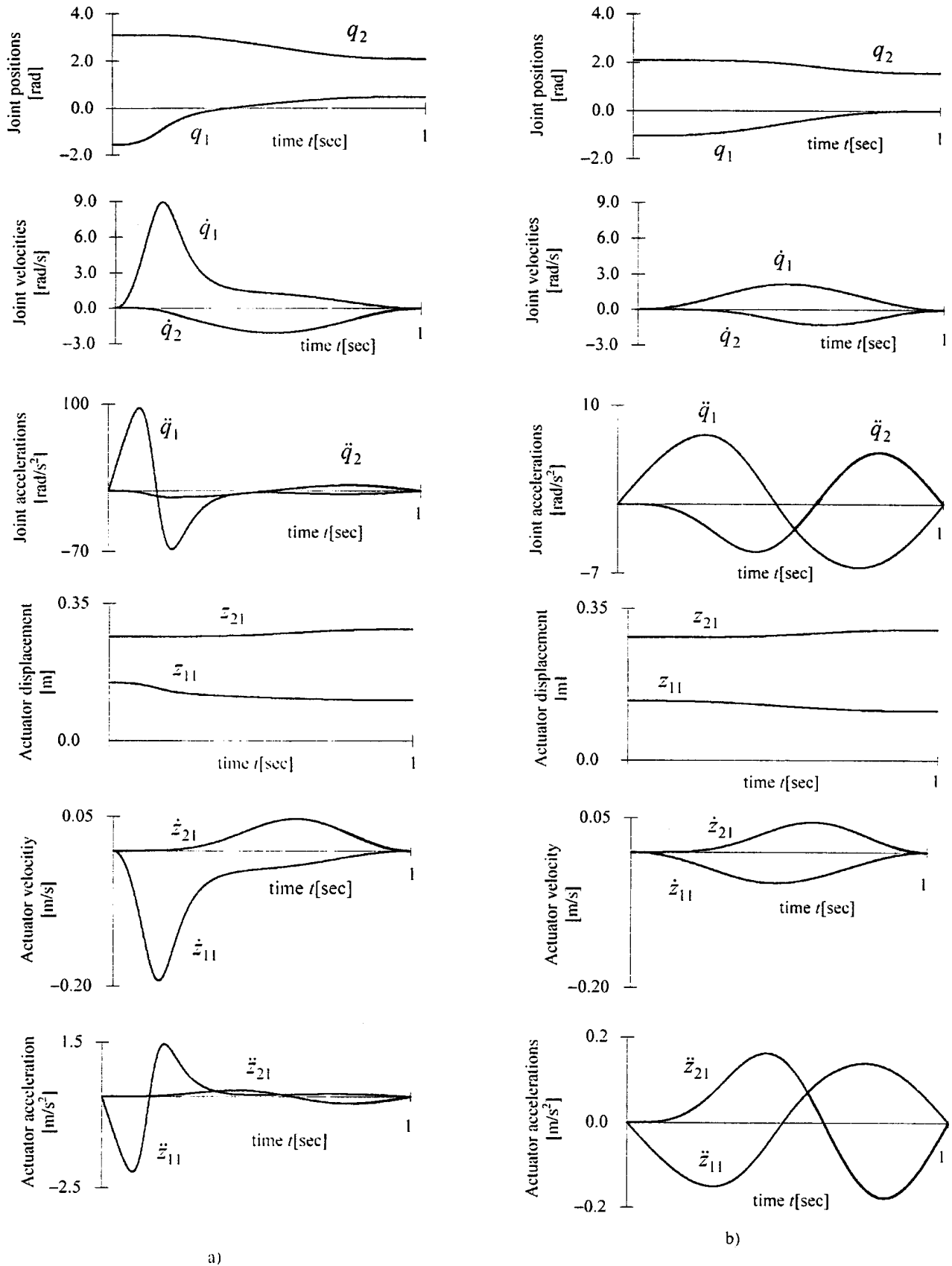


Fig. 5. Time evolution of positions, velocities and accelerations at joints and muscles for trajectories:  
 a)  $s_1$     b)  $s_2$

$$z_{12} = h[2\pi - q_{02} - \sin^{-1}(\sqrt{d^2 - h^2}/d)] + \sqrt{d^2 - h^2} \dots \dots \dots (5a)$$

$$\dot{z}_{12} = -h\dot{q}_{02} \dots \dots \dots (5b)$$

$$\ddot{z}_{12} = -h\ddot{q}_{02} \dots \dots \dots (5c)$$

For the elbow articulation acting in the sagittal plane ( $0 \leq q_2 \leq \pi$ ), we can also derive the expressions for the displacements, velocities and accelerations ( $z_{2i}, \dot{z}_{2i}, \ddot{z}_{2i}$ ) for the biceps brachii and triceps brachii ( $i = 1, 2$ ), yielding:

$$z_{2i} = \sqrt{l_1^2 + b_i^2 + 2l_1b_iC_2} \dots \dots \dots (6a)$$

$$\dot{z}_{2i} = -(l_1b_i S_2/z_{2i}) \dot{q}_2 \dots \dots \dots (6b)$$

$$\ddot{z}_{2i} = -\frac{l_1b_i}{z_{2i}} \left[ C_2 + l_1b_i \left( \frac{S_2}{z_{2i}} \right)^2 \dot{q}_2^2 + S_2\ddot{q}_2 \right] \dots \dots \dots (6c)$$

where  $b_i$  is a parameter.

Comparing the Eq.(1) to Eq.(6) we conclude that the elbow muscle velocities, in Eq.(6b), compensate the factor  $S_2^{-1}$ , present in the conventional inverse kinematics, in Eq.(1b), of joint-actuated systems, that degrades the robot performances near singular points.

### 3. Kinematic Performance of Muscle-Actuated Arms

In this section we analyze the kinematics performances of muscle-actuated arms. We must note that we are not modeling the muscle properties but, in fact, we are proceeding in the opposite way. By other words, we describe the task requirements and the manipulator structure and we study its effect on the actuators. In this perspective, we assume that natural evolution should lead to muscles having properties well matched to the requirements.

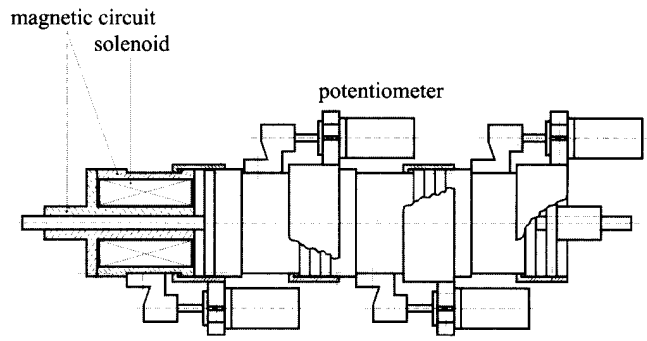
In the experiments we "stimulate" the system through simple trajectories in the operational space and we compare the actuator kinematic variables for the joint-driven and muscle-driven robotics structures. In order to test the biomechanical model we decided to move the arm according with two different linear trajectories in the operational space:

$$s_1: (p_{1a}, p_{2a}) \equiv (0.01, 0) \rightarrow (p_{1b}, p_{2b}) \equiv (0.01, 0.30)$$

$$s_2: (p_{1a}, p_{2a}) \equiv (0.30, 0) \rightarrow (p_{1b}, p_{2b}) \equiv (0.30, 0.30)$$

where  $(p_{1a}, p_{2a})$  and  $(p_{1b}, p_{2b})$  are the coordinates of the initial and final trajectory points, respectively.

Trajectory  $s_1$  starts near the singular point (0,0) while  $s_2$  is less demanding because is far away from singularities. Moreover, the trajectories have identical time evolution:



**Fig. 6.** Solenoid series for robotic application. Each "cell" has:  $R = 23.83\Omega$ ,  $L = 1.88 \text{ mH}$ ,  $A = 19.35 \cdot 10^{-4} \text{ m}^2$ , Weight = 0.55 Kg.

$$s_i : (p_{1a}, p_{2a}) \rightarrow (p_{1b}, p_{2b}) \dots \dots \dots (7a)$$

$$s(t) = \frac{D}{T} \left[ t - \frac{T}{2\pi} \sin\left(\frac{2\pi}{T}t\right) \right] \dots \dots \dots (7b)$$

$$D = \sqrt{(p_{1a} - p_{1b})^2 + (p_{2a} - p_{2b})^2} \dots \dots \dots (7c)$$

where  $T$  is the time duration of movement.

Figure 5 compares the time evolution of  $\{q_i(t), \dot{q}_i(t), \ddot{q}_i(t)\}$  and  $\{z_i(t), \dot{z}_i(t), \ddot{z}_i(t)\}$  for  $s_1$  and  $s_2$  and  $T = 1$  sec. As expected, the results reveal that:

- The joint velocity and acceleration  $\dot{q}_i(t), \ddot{q}_i(t)$ , ( $i = 1, 2$ ), attain higher levels for  $s_1$  than for  $s_2$ .
- The displacement of shoulder and elbow muscles,  $z_{11}(t)$  and  $z_{21}(t)$ , are very limited for both trajectories, being amplified by anatomic levers to produce displacement in operational space.
- The velocity of the elbow muscle,  $\dot{z}_{21}(t)$ , is not sensitive to the singularity near  $s_1$  and gives similar values for  $s_2$ .
- The velocity of the shoulder muscle,  $\dot{z}_{11}(t)$ , is sensitive to the change from  $s_1$  to  $s_2$ .
- The acceleration of shoulder and elbow muscles  $\ddot{z}_{11}(t)$  and  $\ddot{z}_{21}(t)$ , are sensitive to the type of trajectory.

In conclusion, joint actuators, which are developments of standard driving machines that are designed for steady-state applications, are not well adapted to robotic applications. Manipulators must have transmission levers that adapt the operational space tasks to the muscle actuator requirements.

### 4. Linear Actuators for Robot Manipulators

Muscle-driven manipulators require the development of appropriate linear actuators. Such actuators must provide high forces and high accelerations while driving

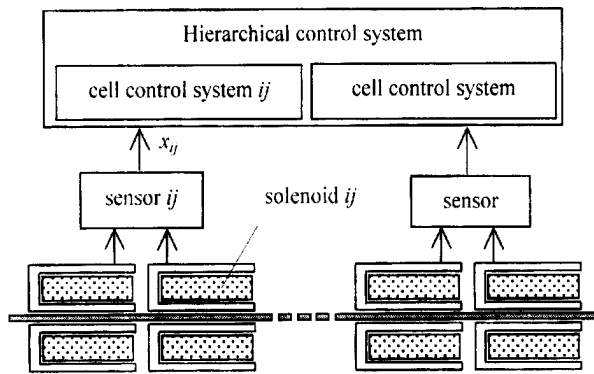


Fig. 7. Actuator hierarchical control system

small displacements. Moreover, in order to simplify the interface with the control system, an electrical actuator will be preferable. In this line of thought, a servo-solenoid is an electromagnetic equivalent of a muscle cell, and it can be modeled through the equations:

$$v = Ri + Li + K_b \dot{x} \dots \dots \dots (8a)$$

$$f = K_f A \left( \frac{Ni}{x} \right)^2 \dots \dots \dots (8b)$$

Here  $R$  and  $L$  represent the resistance and inductance of the coil,  $N$  the number of turns,  $A$  and  $x$  are the area and length of the air gap in the magnetic circuit. The electrical voltage and current are  $v$  and  $i$ , the force exerted of the moving part of the solenoid is  $f$  and  $K_b$  and  $K_f$  are constants of proportionality.

The development of a linear electromagnetic actuator is currently under development (Fig.6).

As solenoids represent a mimic of muscles they can be associated in  $u$  series and in  $w$  parallels leading to the expressions for the total force  $F_{Total}$  and displacement  $X_{Total}$

$$F_{Total} = \sum_{i=1}^w Min(F_{ij}) \dots \dots \dots (9a)$$

$$X_{Total} = \sum_{j=1}^u Min(x_{ij}) \dots \dots \dots (9b)$$

Such associations allow the minimization of the actuator moving inertia and the allocation of different "cells" to distinct operating conditions (e.g. transient versus steady-state) in a hierarchical control system (Fig. 7).

### 5. Conclusions

The paper presented the analysis of mechanical manipulators in the sagittal plane. Motivated by the kinesiological aspects of the human arm we demonstrate that

biomechanical structures have better performances than standard robot manipulators. In fact, joint-actuated robotic structures are non-optimal because they have to support the direct impact of the operational requirements, while muscle-actuated arms are superior because they have anatomic levers and actuators more adapted to the transients required by the operational tasks. Therefore, these results are a step towards the design of a new generation of better manipulators structures and a new generation of linear muscle-like, low displacement high acceleration, actuators. In this perspective, it is proposed the adoption of solenoids as electromagnetic actuators that provide high forces and small displacements. Its dynamic characteristics are nonlinear and present challenging aspects in what concerns the control system that is presently under study.

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