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A BIOMECHANICAL PERSPECTIVE FOR THE KINEMATIC ANALYSIS OF ROBOT MANIPULATORS

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Mechanical manipulators are described through mathematical models based on the formalisms of the classical physics. The kinematic and dynamic models allow the study of the phenomena involved, but are complex to tackle at a design stage. As a consequence, present day robotic structures 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 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.

Keywords: Robotics; 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 design of direct drive robots [1], the study of lightweight flexible manipulators [2] and the development of mathematical and computer models of the kinematic and dynamic phenomena [3–8]. Nevertheless, clear guidelines towards the implementation of optimal manipulating structures are still lacking. Joint-

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driven manipulators, with standard actuators, are not well adapted to the transients imposed by the robotic applications. In this perspective, alternative structures having muscle-like actuators and appropriate mechanical levers, allow more efficient robotic manipulators. This paper analyses the properties of the kinematic biomechanical-like arms and is organized as follows. Section two addresses the kinesiological aspects of the human arm. Based on these considerations, section three formulates the corresponding geometrical and mathematical models. Section four shows the performances of muscle-actuated manipulators. Finally, section five outlines the main conclusions.

2. BIOMECHANICS OF THE HUMAN ARM

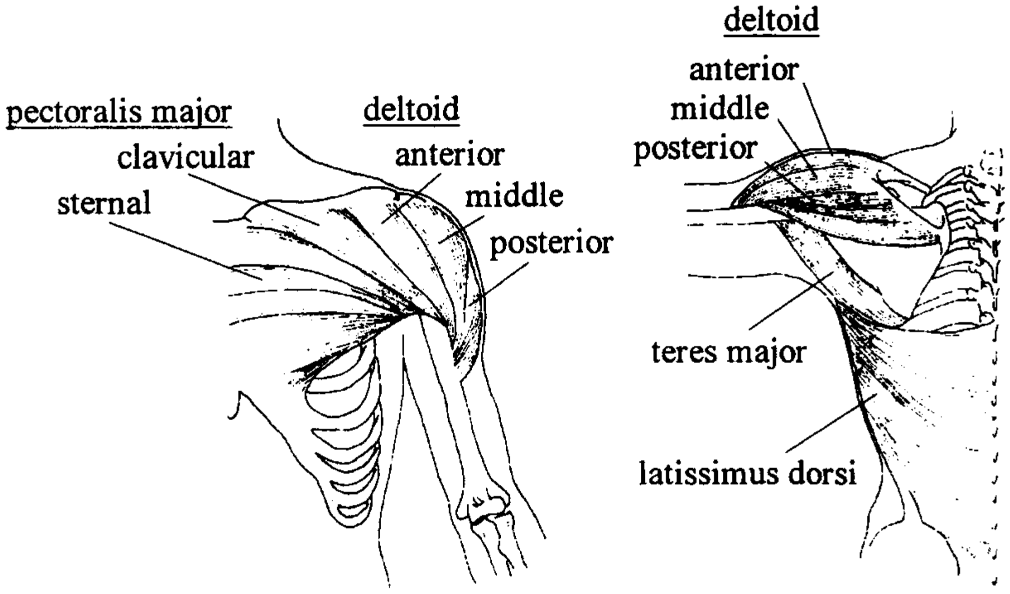
Robotic manipulators are described through the kinematic and dynamic models. These models relate positions, velocities, accelerations and forces/torques on the operational $\{\mathbf{p}, \dot{\mathbf{p}}, \ddot{\mathbf{p}}, \Gamma\}$ and joint $\{\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}, \mathrm{T}\}$ spaces. However, standard modeling techniques, based on the laws of Euclidean geometry and classical mechanics, conduce to intricate formulae, which are difficult to study. Due to this reason, there are, not yet, systematic and clear algorithms towards the design of optimal structures. In fact, joint-actuated manipulators, driven by standard actuators, may not be well adapted to the transients imposed by the operational tasks [9, 10]. Therefore, alternative solutions based on muscle-like actuators [11–14], allow more efficient manipulating structures. Having these ideas in mind, in this section we address the kinesiological aspects of the human arm in order to design a geometrical model that reflects its main characteristics.

Extensive studies [15–26] have been carried out on this subject, still there are not definite conclusions. Therefore, in order to simplify matters, only the motion in the sagittal plane will be considered. Moreover, a simple observation reveals that, at the biomechanical level, the human arm is driven by two main articulations: the shoulder and the elbow [27, 28]. Consequently, the study of these articulations is the subject of the next two sub-sections. As muscles are unidirectional actuators, articulations are driven by pairs of antagonist muscles that are activated, alternatively, during flexion and extension. In this perspective, both the shoulder and elbow structures reflect this characteristic.

2.1. The Shoulder Articulation

The shoulder actuation involves a multitude of muscles that are distributed through the sternoclavicular, acromioclavicular and glenohumeral structures (Figs. 1 and 2).

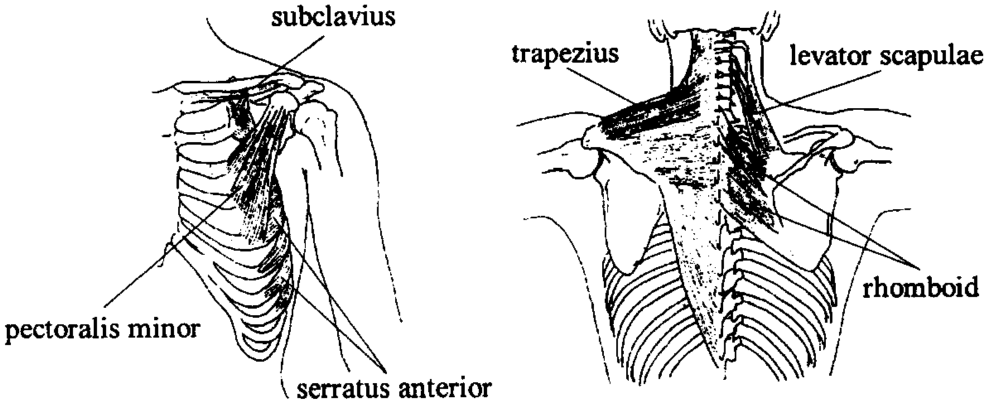
Figure 3 shows the force system and the main muscles involved during the flexion.



Anterior view

Posterior view

FIGURE 1 Muscles of the shoulder girdle (acromioclavicular and sternoclavicular articulations).



Anterior view

Posterior view

FIGURE 2 Muscles of the shoulder joint (glenohumeral articulation).

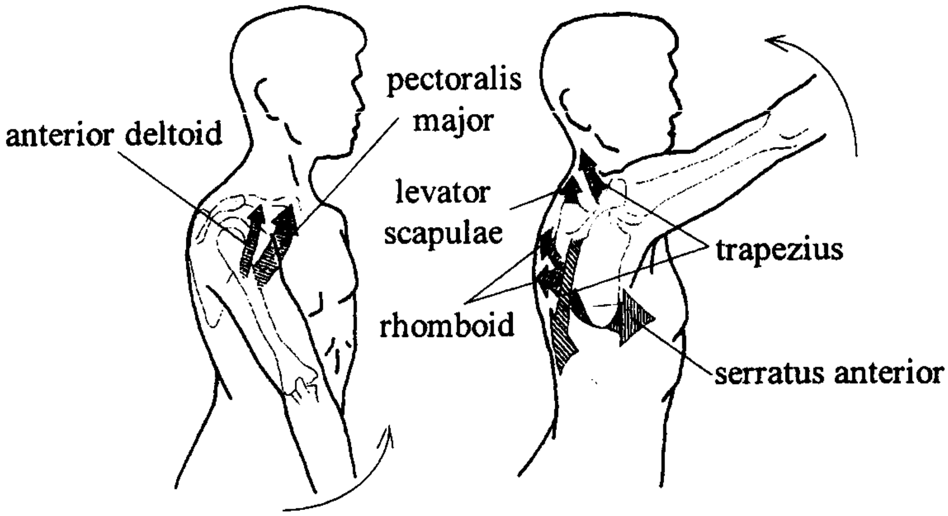


FIGURE 3 Forces that occur at the shoulder joint during the flexion in the sagittal plane.

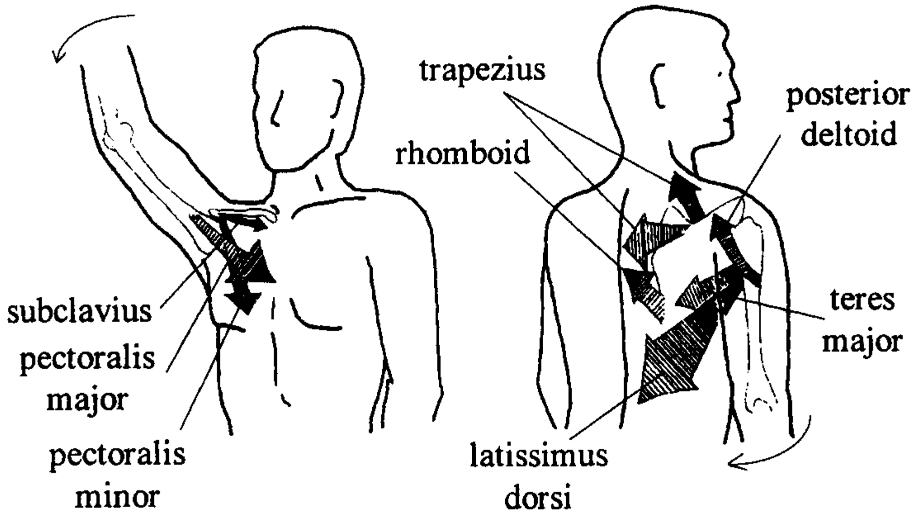


FIGURE 4 Forces that occur at the shoulder joint during the extension in the sagittal plane.

For the extension, the forces and muscles involved are depicted on Figure 4.

2.2. The Elbow Articulation

The elbow reveals a much more simple structure than the shoulder. For the movement of the elbow in the sagittal plane, 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 (Fig. 5).

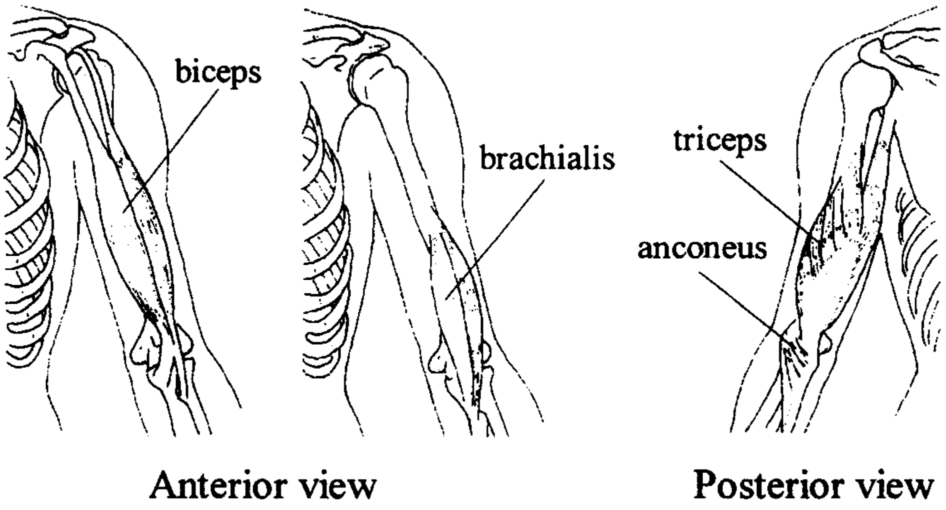


FIGURE 5 Muscles of the elbow joint.

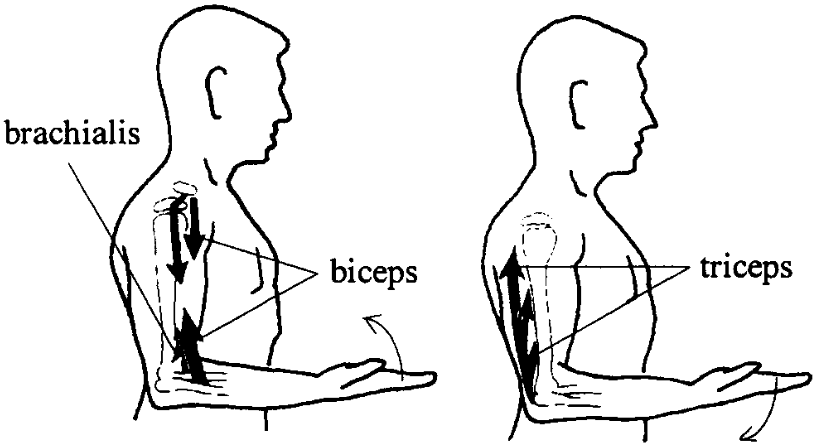


FIGURE 6 Forces that occur at the elbow joint during the flexion and extension in the sagittal plane.

Figure 6 shows the force system for the flexion (biceps brachii activated) and the extension (triceps brachii activated).

3. A GEOMETRIC MODEL OF THE HUMAN ARM

Based on the analysis of the main biological phenomena involved in the human arm, in this section we develop a geometric model for the mathematical investigation of the characteristics of a muscle-actuated arm. The two articulation structures, of the shoulder and elbow, are studied in the following sub-sections.

3.1. The Shoulder Structure

Figure 7 shows a simplified geometrical model of this mechanism in the sagittal plane. 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}-flexion or q_{02}-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, the rhomboids, *etc.* For this structure we can derive the expressions of the range of motion, lengths (z_{1i}), velocities ($\dot{z}_{1i}$), accelerations ($\ddot{z}_{1i}$), and forces (F_{1i}) both for anterior ($i = 1$) and the posterior ($i = 2$) deltoids.

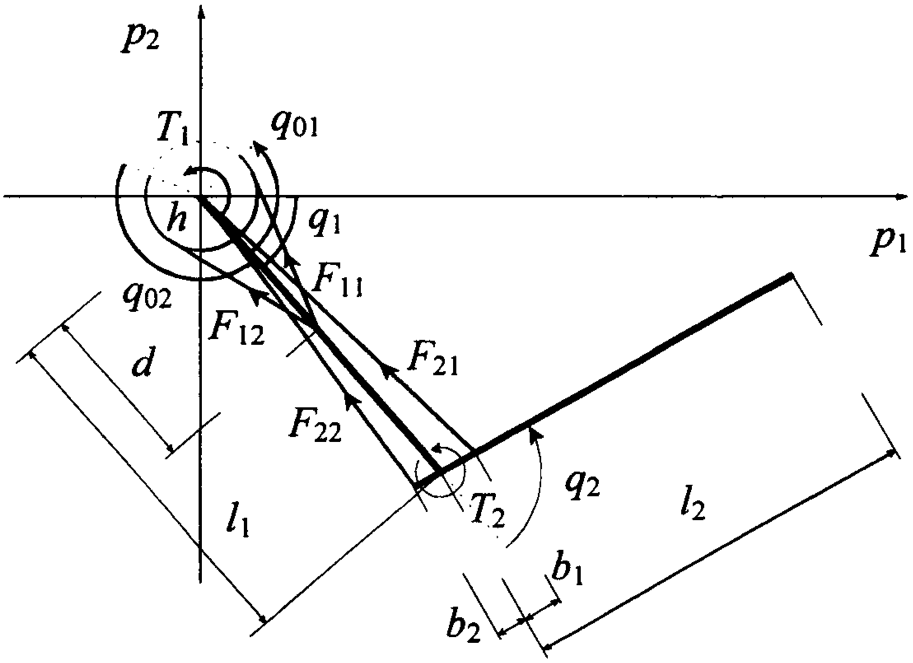


FIGURE 7 Geometrical model of the human arm in the sagittal plane for the shoulder and the elbow structures.

In this model, the kinematic control scheme, that is, the relationship between q_1 and q_{01} or q_{02}, is assumed to obey the equations:

$$q_{01} = \begin{cases} 0.528\pi - 0.5q_1 & -2\pi/3 \leq q_1 < -\pi/2 \\ 0.278\pi - q_1 & -\pi/2 \leq q_1 < -\pi/6 \\ 0.361\pi - 0.5q_1 & -\pi/6 \leq q_1 < \pi/6 \\ 0.411\pi - 0.8q_1 & \pi/6 \leq q_1 \leq 4\pi/9 \end{cases} \tag{1a}$$

$$q_{02} = \begin{cases} 1.083\pi - 0.5q_1 & -2\pi/3 \leq q_1 < -\pi/2 \\ 0.833\pi - q_1 & -\pi/2 \leq q_1 < -\pi/6 \\ 0.917\pi - 0.5q_1 & -\pi/6 \leq q_1 < \pi/6 \\ 0.75\pi + 0.5q_1 & \pi/6 \leq q_1 \leq 4\pi/9 \end{cases} \tag{1b}$$

These equations 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:

- *Case A.1.* The anterior deltoid is wound around the pulley
- *Case A.2.* The anterior deltoid is acting freely (*i.e.*, is not wound around the pulley)

  For the extension we have a single case:
- *Case B.* The posterior deltoid is wound around the pulley throughout the total range of motion

From the geometric model, these cases correspond to the following expressions:

Case A.1. The anterior deltoid is wound around the pulley

$$-2\pi/3 \leq q_1 < -\pi/18 \tag{2a}$$

$$z_{11} = h\left(q_{01} - sin^{-1}\frac{\sqrt{d^2 - h^2}}{d}\right) + \sqrt{d^2 - h^2} \tag{2b}$$

$$\dot{z}_{11} = h\dot{q}_{01} \tag{2c}$$

$$\ddot{z}_{11} = h\ddot{q}_{01} \tag{2d}$$

Case A.2. The anterior deltoid is acting freely

$$-\pi/18 \leq q_1 \leq 4\pi/9 \tag{3a}$$

$$z_{11} = \sqrt{d^2 + h^2 - 2dhC_{01}} \tag{3b}$$

$$\dot{z}_{11} = \frac{dhS_{01}}{z_{11}}\dot{q}_{01} \tag{3c}$$

$$\ddot{z}_{11} = \frac{dh}{z_{11}}\left[\left(\frac{z_{11}^2 C_{01} - dhS_{01}^2}{z_{11}^2}\right)\dot{q}_{01}^2 + S_{01}\ddot{q}_{01}\right] \tag{3d}$$

Case B. The posterior deltoid is wound around the pulley throughout the total range of motion

$$-2\pi/3 \leq q_1 \leq 4\pi/9 \tag{4a}$$

$$z_{12} = h\left(2\pi - q_{02} - sen^{-1}\frac{\sqrt{d^2 - h^2}}{d}\right) + \sqrt{d^2 - h^2} \tag{4b}$$

$$\dot{z}_{12} = -h\dot{q}_{02} \tag{4c}$$

$$\ddot{z}_{12} = -h\ddot{q}_{02} \tag{4d}$$

where h and d are geometrical parameters.

3.2. The Elbow Structure

The movement of the elbow in the sagittal plane (q_2) requires also several muscles. For the geometrical model depicted in Figure 7 we can also derive the expressions for range of motion, lengths (z_{2i}), velocities ($\dot{z}_{2i}$), accelerations ($\ddot{z}_{2i}$), and forces (F_{2i}) for the biceps brachii ($i = 1$) and triceps brachii ($i = 2$):

$$0 \leq q_2 \leq \pi \tag{5a}$$

$$z_{2i} = \sqrt{l_1^2 + b_i^2 + 2l_1 b_i C_2} \tag{5b}$$

TABLE I Inverse kinematics

$$q_2 = \cos^{-1}[(p_1^2 + p_2^2 - l_1^2 - l_2^2)/2l_1 l_2], q_1 = \tan^{-1}(p_2/p_1) - \tan^{-1}[l_2S_2/(l_1 + l_2C_2)]$$

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = 1/l_1 l_2 S_2 \begin{bmatrix} l_2C_{12} & l_2S_{12} \\ -l_1C_1 - l_2C_{12} & -l_1S_1 - l_2S_{12} \end{bmatrix} \begin{bmatrix} \dot{p}_1 \\ \dot{p}_2 \end{bmatrix}$$

$$\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} = 1/l_1 l_2 S_2 \begin{bmatrix} l_2C_{12} & l_2S_{12} \\ -l_1C_1 & -l_1S_1 \end{bmatrix} \begin{bmatrix} \ddot{p}_1 \\ \ddot{p}_2 \end{bmatrix} + 1/l_1 l_2 S_2 \begin{bmatrix} l_1 l_2 C_2 & l_2^2 \\ -l_1^2 & -l_1 l_2 C_2 \end{bmatrix} \begin{bmatrix} \dot{q}_1^2 \\ \dot{q}_{12}^2 \end{bmatrix}$$

$$\dot{z}_{2i} = -\frac{l_1 b_i S_2}{z_{2i}} \dot{q}_2 \tag{5c}$$

$$\ddot{z}_{2i} = -\frac{l_1 b_i}{z_{2i}} \left\{ C_2 + l_1 b_i \left(\frac{S_2}{z_{2i}} \right)^2 \dot{q}_2^2 + S_2 \ddot{q}_2 \right\} \tag{5d}$$

were b_i is a parameter. Equation (5c), for the velocities of the elbow muscles, reveals that the (degrading) factor S_2^{-1}, which affects the inverse kinematic transformation (Tab. I) of joint-actuated robots, is now compensated.

We also conclude that the shoulder and elbow structures have different anatomic levers that adapt the operational exigencies to the muscle requirements. In fact, the elbow levers seem more efficient because they compensate muscle velocities near the singular points $q_2 = \{0, \pm\pi\}$. Therefore, either the geometric model of the shoulder is incomplete, and the kinesiological structure has built-in further compensation schemes, or the shoulder is an articulation that poses requirements to the muscles that are superior of those imposed to the elbow actuators. A sounder conclusion about this aspect needs further investigation at the biological level and, at this time, is still not available. Nevertheless, we conclude that, whatever be the case, the shoulder structure is far more complex than the elbow structure, which is in accordance with the previous study of Section 2.

4. 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, $s_1:(0.01,0)\rightarrow(0.01,0.3)$ and $s_2:(0.3,0)\rightarrow(0.3,0.3)$, where (x_1,y_1) and (x_2,y_2) are the coordinates of the initial and final points of each trajectory. Therefore, the s_1 trajectory 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:

$$\ddot{s}(t)=\frac{D\omega}{T}\sin(\omega t) \tag{6a}$$

$$\dot{s}(t)=\frac{D}{T}[1-\cos(\omega t)] \tag{6b}$$

$$s(t)=\frac{D}{T}[t-\omega^{-1}sen(\omega t)] \tag{6c}$$

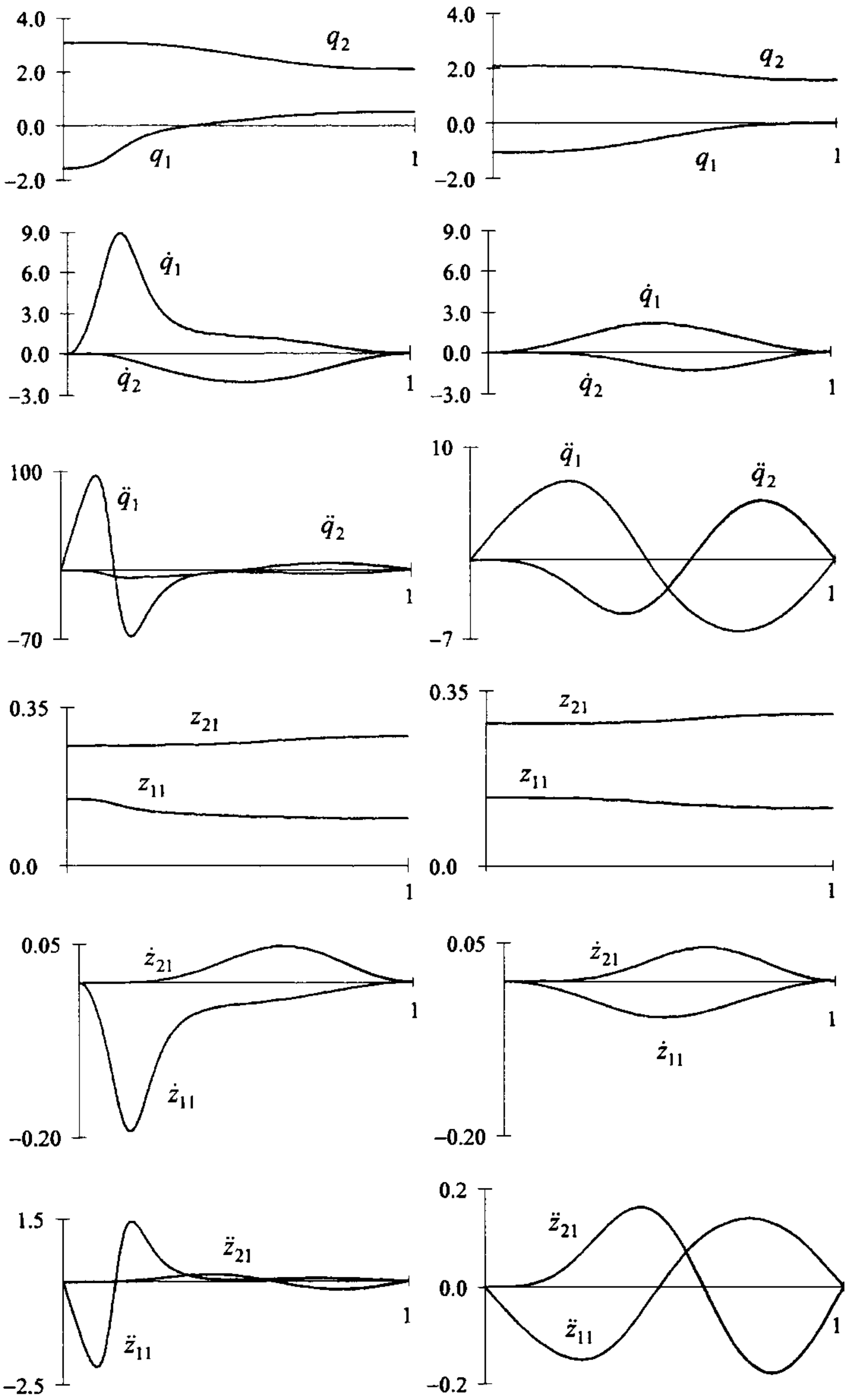
$$D=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2} \tag{6d}$$

$$\omega=2\pi/T \tag{6e}$$

where T is the total time of the movement. For $T=1$ and the numerical parameters of Table II Figure 8 compares the time evolution of $\{q_i(t),\dot{q}_i(t),\ddot{q}_i(t)\}$ and $\{z_{i1}(t),\dot{z}_{i1}(t),\ddot{z}_{i1}(t)\}$ (to simplify, only the requirements to the flexion actuators are depicted) for s_1 and s_2.

TABLE II Parameters of the muscle actuated manipulator

$l_1=0.3\,\mathrm{m}$, $l_2=0.3\,\mathrm{m}$, $d=0.126\,\mathrm{m}$, $h=0.043\,\mathrm{m}$, $b_1=0.034\,\mathrm{m}$, $b_2=-0.02\,\mathrm{m}$



a) b)

FIGURE 8 Time evolution of positions, velocities and accelerations at the joints and muscles for trajectories: (a) s_1; (b) s_2.

As expected, the results reveal that:

- The joint velocities and accelerations, $\dot{q}_i(t)$, $\ddot{q}_i(t)$, $(i = 1, 2)$, attain higher levels for s_1 than for s_2.
- The displacements of the shoulder and elbow muscles, $z_{11}(t)$ and $z_{21}(t)$, are very limited for both trajectories, being amplified by the anatomic levers in order to produce the displacement $\{p_1(t), p_2(t)\}$ in the 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 s_1 to s_2.
- The accelerations of the shoulder and elbow muscle, $\ddot{z}_{11}(t)$ and $\ddot{z}_{21}(t)$, are sensitive to the type of trajectory.

These observations reveal that a robot is by excellence a "transient machine" and not a "steady-state machine". Therefore, usual joint actuators, which are developments of standard driving machines that are designed for steady-state applications, are not well adapted to robotic applications. From a biological point of view, manipulators must have anatomic levers that adapt the operational space tasks to the muscle driving requirements. Furthermore, these biological-like actuators should have characteristics of low linear displacements, low velocities and high accelerations.

5. CONCLUSIONS

The paper presented the analysis of biomechanical manipulators in the sagittal plane. Motivated by the kinesiological aspects of the human arm we demonstrate that biomechanical structures have better performances than standard mechanical 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.

References

[1] Asada, H. and Youcef-Toumi, K. (1984). Analysis and design of a direct-drive arm with a five-bar-link parallel mechanism, *ASME J. Dynamic Syst., Meas., Contr.*, **106**, 225–230.

[2] Rovner, D. M. and Cannon, R. H. Jr. (1987). Experiments toward on-line identification and control of a very flexible one-link manipulator, *The Int. J. Robotics Research*, **6**, 3–19.

[3] Tsai, Y. C. and Soni, A. H. (1981). Accessible region and synthesis of robot arms, *ASME J. Mechanical Design*, **103**, 803–811.

[4] Asada, H. (1983). A Geometrical representation of manipulator dynamics and its application to arm design, *ASME J. Dynamic Syst., Meas., Contr.*, **105**, 131–142.

[5] Yoshikawa, Tsuneo (1985). Manipulability of robotic mechanisms, *The Int. J. Robotics Research*, **4**, 3–9.

[6] Yoshikawa, T. (1986). Analysis and design of articulated robot arms from the viewpoint of dynamic manipulability, *Robotics Research, The Third Int. Symp.*, MIT Press, pp. 273–279.

[7] Yang, D. C. H. and Tzeng, S. W. (1986). Simplification and linearization of manipulator dynamics by the design of inertia distribution, *The Int. J. Robotics Research*, **5**, 120–128.

[8] Youcef-Toumi, K. and Asada, H. (1987). The design of open-loop manipulator arms with decoupled and configuration-invariant inertia tensors, *ASME J. Dynamic Syst., Meas., Contr.*, **109**, 268–275.

[9] Galhano, Alexandra M. S. F., Machado, J. A. T. and de Carvalho, J. L. M. (1991). On the statistical modelling of mechanical manipulators, *SYROCO'91-IFAC Symp. on Robot Control*, pp. 15–20, Vienna, Austria.

[10] Tenreiro Machado, J. A. and Galhano, Alexandra M. S. F. (1993). Statistical modelling of robotic manipulators, *SAMS* – Journal Systems Analysis-Modelling Simulation, Gordon and Breach Science Publishers, **12**, 101–123.

[11] De Rossi, D., Domenici, C. and Chiarelli, P. (1986). Analogs of biological tissues for mechanoelectrical transduction: tactile sensors and muscle-like actuators, NATO ARW on Sensors and Sensory Systems for Advanced Robots, Italy.

[12] Kuribayashi, K. (1986). A new actuator of a joint mechanism using TiNi alloy wire, *The Int. J. Robotics Research*, **4**, 47–58.

[13] Tatara, Y. (1987). Mechanochemical actuators, *Advanced Robotics*, **2**, 69–85.

[14] Caldwell, D. G. and Taylor, P. M. (1988). Artificial muscles as robotic actuators, *SYROCO'88-IFAC Symp. on Robot Control*, pp. 40.1–40.6, Karlsruhe, Germany.

[15] Kendall, H. O., Kendall, F. P. and Wadsworth, G. E. (1971). Muscles-Testing and function, The Williams and Wilkins Company, Baltimore, USA.

[16] Wells, K. F. and Luttgens, K. (1976). Kinesiology-Scientific basis of human motion, W. B. Saunders Company.

[17] Rasch Philip, J. and Roger, K. Burke (1976). Kinesiology and applied anatomy-The Science of human movement, Lea and Febiger, Philadelphia, USA.

[18] Fischer, L. P., Carret, J. P., Gonnon, G. P. and Dimnet, J. (1977). Étude cinématique des mouvements de l'articulation scapulo-humérale (articulatio humeri), *Rev. Chir. Orthop.*, **63**, 108–112.

[19] Ito, N., Suzuki, R., Ishimura, K. and Kuwahara, H. (1979). Electromyographic study of shoulder joint, *4th Congress of I.S.E.K.*, pp. 22–23, Boston, USA.

[20] An, K. N., Hui, F. C., Morrey, B. F., Linscheid, R. L. and Chao, E. Y. (1981). Muscles across the elbow joint: a biomechanical analysis, *J. of Biomechanics*, **14**, 659–669.

[21] Kinzel, G. L. (1982). Reduction of instrumental linkage data for simple anatomical joint models, *ASME J. Mechanical Design*, **104**, 218–226.

[22] Kapandji, I. (1983). Physiologie articulaire-Schémas commentés de mécanique humaine-Tome 1, Membre supérieur, Maloine S. A. (Ed.).

[23] Hogan, N. (1984). Adaptive Control of Mechanical impedance by coactivation of the antagonist muscles, *IEEE Trans. Automat. Contr.*, **29**(8), 681 – 690.

[24] Atkeson, C. G. and Hollerbach, J. M. (1985). Kinematic features of unrestrained vertical arm movements, *J. Neuroscience*, **5**(9), 2319 – 2330.

[25] Akazawa, K. and Fujii, K. (1986). Theory of muscle contraction and motor control, *Advanced Robotics*, **1**, 379 – 390.

[26] Kawato, M. (1989). Adaptation and learning in control of voluntary movement by the central nervous system, *Advanced Robotics*, **3**(3), 229 – 249.

[27] Galhano, Alexandra M. S. F., Tenreiro Machado, J. A. and Martins de Carvalho, J. L. (1991). On the analysis of muscle-actuated manipulators, *ICAR'91-Fifth. Int. Conf. on Advanced Robotics*, pp. 67 – 71, Pisa, Italy.

[28] Galhano, Alexandra M. S. F., Tenreiro Machado, J. A. and Martins de Carvalho, J. L. (1992). Statistical analysis of muscle-actuated manipulators, *ICRA'92-IEEE Int. Conf. on Robotics and Automation*, pp. 332 – 337, Nice, France.