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THE STATISTICAL STUDY OF BIOMECHANICAL ARMS

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Abstract

In a companion paper a statistical method for the analysis and design of robot manipulators was presented. The new formalism revealed the limitations of standard joint-actuated mechanical manipulators. Stemming from those results, in this paper we apply the new modelling concepts on the study of biological arms. The superior performances of muscle-actuated arms over standard joint-actuated manipulators are clearly demonstrated. These results are of utmost importance as they give a clear basis to the design of new mechanical robotic structures, with performances close to the biological systems.

Introduction

Robotic mechanisms are essential blocks in modern automatic systems. Human activities adopt inherently anthropomorphic concepts and therefore, they lead to the requirement for tools and processes according to these principles. In this sense, a robot manipulator is a tool that extends the human capabilities having the human arm as its reference concept. However, this observation is confronted with the present day situation where robot technology makes an insignificant appeal to the biomechanical aspects of the human arm.

The problem resides on the development of mathematical tools well adapted to the study of both mechanical and biological systems. In a companion article [1] we developed a method for the analysis of robotic manipulators. Using the new formalism, based on statistical concepts, we revealed the limitations of joint-actuated mechanical manipulators. Motivated by this study, in this paper we apply the statistical method to the analysis of biomechanical arms.

In section two we begin by studying the kinesiological aspects of the human arm. Based on this study, we develop an engineering formulation of the corresponding system. In section three we use the statistical method on the analysis of muscle-actuated manipulators. The superior performances of these structures over standard joint-actuated ones is thereafter clearly demonstrated. Finally, in section four we present some global conclusions.

Characteristics of the Human Arm and its Engineering Formulation

Mechanical manipulators are described through the so-called kinematic and dynamic models. These models relate positions, velocities, accelerations and forces/torques on the operational $\{p, \dot{p}, \ddot{p}, \Gamma\}$ and joint spaces $\{q, \dot{q}, \ddot{q}, T\}$. For a n degrees of freedom manipulator each joint torque T_i $(i=1,\ldots n)$ has an intricate relationship with the other variables. Due to this reason clear guidelines for the implementation of optimal manipulator structures are still lacking. The authors developed a method, based on statistical concepts [2], that overcomes these difficulties. Such studies proved that mechanical joint-actuated manipulators are much more sensitive to velocity requirements than to acceleration requirements. In fact, we are dealing with "position and acceleration machines" rather than "velocity machines". Although obvious, this aspect has been somewhat overlooked. Moreover, it points out that the usual robot actuators, which are developments of standard "velocity machines" are not well adapted to robotic applications. Alternative solutions, such as muscle like "position and acceleration" actuators [3-6] will allow more efficient robot structures [7]. In this section we introduce several biomechanical concepts and we design a (simplified) engineering structure corresponding to the human arm.

The human arm may be considered as the optimal manipulator and, therefore, it will constitute our reference. Extensive biological studies [8-15] have been carried out on this subject. Unfortunately, precise conclusions on all of the involved phenomena are still lacking. Due to this reasons, before proceeding to the design of an engineering structure "equivalent" to the human arm we will have to put forward several hypothesis. These hypothesis on the functioning of the human arm are based on the available kinesiological data. Furthermore, in order to simplify matters, solely the motion in the sagittal plane will be considered on the analysis of the shoulder and elbow structures. We start by analysing, in the first sub-section, the shoulder structure while, in the second sub-section, we study the elbow structure.

The Shoulder Structure

The shoulder structure is composed of two major systems: the shoulder joint and the shoulder girdle. Kinesiological studies show that the move-

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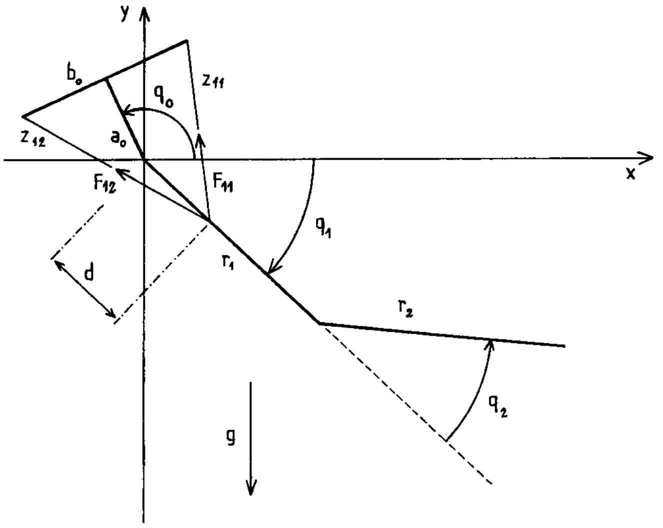

Fig. 1 Engineering model of the shoulder structure in the sagittal plane.

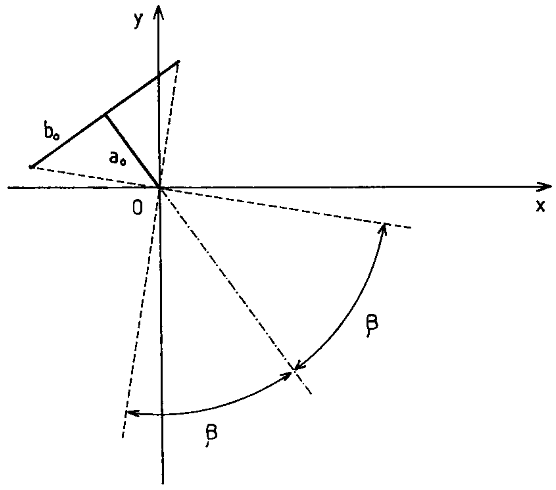

Fig. 2 Relationship between the geometry of the T-structure and the range of motion of q_1.

ment of these systems involve a plethora of muscles. The shoulder actuation in the sagittal (or antero-posterior) plane requires the following muscles:

• Forward Elevation - Shoulder joint: Anterior deltoid, pectoralis major (clavicular portion).

• Forward Elevation - Shoulder girdle: Serratus anterior, trapezius, levator scapulae and rhomboids.

• Forward-Downward Depression and Backward Elevation - Shoulder joint: Posterior deltoid, latissimus dorsi, teres major and pectoralis major (sternal portion).

• Forward-Downward Depression and Backward Elevation - Shoulder girdle: Pectoralis minor, trapezius, rhomboids and subclavius.

These muscles are distributed through the so-called sternoclavicular, the acromioclavicular and the glenohumeral structures which constitute the shoulder mechanism. Such distribution leads to a reduction on the exigencies posed to the muscles. In fact, this anatomic arrangement accounts for:

• The avoidance of logistic problems such as the obstruction of the arm movements.

• The extensive freedom of motion enjoyed by the upper arm.

• The existence of anatomic-levers which adapt the operational motion exigencies up to the muscle actuation requirements.

Figure 1 represents a simple engineering model of this anatomic mechanism in the sagittal plane. The anterior and posterior deltoids actuate the shoulder joint and have insertions both on the humerus and the T-structure. Here, the T-structure accounts for the scapulae, the clavicle, the sternum and the trunk, and has an independent motion (q_o) of the humerus movement (q_1). By other words, the relative position of the humerus and the T-structure is controlled by the pair of deltoids, while the (absolute) position of the T-structure is controlled by muscles such as the serratus anterior, the trapezius, the rhomboids etc.

For this structure we have:

$$z_{11}=[(a_oC_o+b_oS_o-dC_1)^2+(a_oS_o-b_oC_o-dS_1)^2]^{1/2} \quad (1a)$$

$$z_{12}=[(a_oC_o-b_oS_o-dC_1)^2+(a_oS_o+b_oC_o-dS_1)^2]^{1/2} \quad (1b)$$

$$\dot{z}_{11}=[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1-\beta)/z_{11}](\dot{q}_o-\dot{q}_1) \quad (2a)$$

$$\dot{z}_{12}=[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1+\beta)/z_{12}](\dot{q}_o-\dot{q}_1) \quad (2b)$$

$$\ddot{z}_{11}=[d(a_o^2+b_o^2)^{1/2}z_{11}^2COS(q_o-q_1-\beta)-d^2(a_o^2+b_o^2)SIN^2(q_o-q_1-\beta)](\dot{q}_o-\dot{q}_1)^2/z_{11}^3+ +[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1-\beta)](\ddot{q}_o-\ddot{q}_1)/z_{11} \quad (3b)$$

$$\ddot{z}_{12}=[d(a_o^2+b_o^2)^{1/2}z_{12}^2COS(q_o-q_1+\beta)-d^2(a_o^2+b_o^2)SIN^2(q_o-q_1+\beta)](\dot{q}_o-\dot{q}_1)^2/z_{12}^3+ +[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1+\beta)](\ddot{q}_o-\ddot{q}_1)/z_{12} \quad (3b)$$

$$F_{11}=T_1z_{11}/[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1-\beta)] \quad (4a)$$

$$F_{12}=T_1z_{12}/[d(a_o^2+b_o^2)^{1/2}SIN(q_o-q_1+\beta)] \quad (4b)$$

$$\beta=TAN^{-1}(b_o/a_o) \quad (5)$$

where z_{1i}, $\dot{z}_{1i}$, $\ddot{z}_{1i}$ and F_{1i} are the length, velocity, acceleration and force on the anterior (i=1) and posterior (i=2) deltoids, and β is a parameter that characterizes the geometry of the T-structure.

Two major observations can be drawn:

• 2β gives a measure of the range of motion generated by the deltoids (Fig. 2). A wide range of operation requires a large β; nevertheless, values of β near π/2 should be avoided as they imply $b_o/a_o \to \infty$ which is impractical. Therefore, a large range of operation must be achieved at the cost of a shoulder control strategy rather than at the cost of anatomical dimensions.

• The control scheme that is, the relationship between the position of the humerus (q_1) and the position of the T-structure (q_o) can be found if we analyse:

i) The limit range of motion of both structures

$$q_{oMAX}-q_{oMIN}+2\beta=q_{1MAX}-q_{1MIN} \quad (6)$$

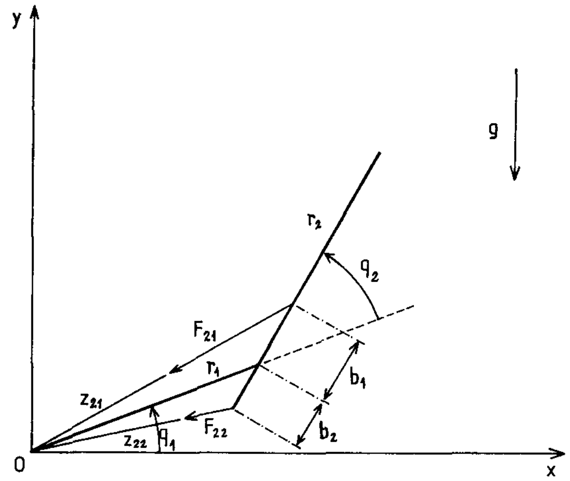

Fig. 3 Engineering model of the elbow structure in the sagittal plane.

where q_{0MAX} and q_{0MIN} (q_{1MAX} and q_{1MIN}) correspond to the upper and lower limits of the range of motion of the first link (T-structure).

ii) The middle point of the range of motion of each structure

$$(q_{0MAX}+q_{0MIN})/2+\pi=(q_{1MAX}+q_{1MIN})/2 \quad (7)$$

Knowing that for the human arm we have approximately:

$$q_{1MAX}=-5\pi/6,\ q_{1MIN}=\pi/6 \quad (8)$$

then, a synchronized motion of both structures that is, attaining simultaneously the upper or lower limits of the corresponding ranges of variation, requires:

$$\beta=\pi/4 \quad (9)$$
$$\dot q_0=\dot q_1/2 \quad (10)$$

These values (9)-(10) are consistent with the available data on the motion of the human shoulder. Moreover, expression (10) represents a compromise between the minimization of the humerus actuator (i.e. the deltoids) requirements in (2)-(3) and the T-structure actuator (i.e. the serratus anterior, the trapezius, the rhomboids etc.) requirements.

The Elbow Structure

The elbow movement in the sagittal plane (q_2) requires also several muscles namely:

- Flexion: Biceps brachii, brachialis and brachioradialis.
- Extension: Triceps brachii and anconeus.

Considering only the biceps brachii and the triceps brachii, as they are the more influential, Fig. 3 shows its simplified engineering model. For this structure we have (i=1,2):

$$z_{2i}=(r_1^2+b_i^2+2r_1b_iC_2)^{1/2} \quad (11)$$

TABLE 1 Numerical characteristics of the human arm

a_0=0.0218 m, b_0=0.0218 m, d=0.1164 m
b_1=0.05m, b_2=-0.02 m, R_1=0.05 m, R_2=0.0389 m
r_1=0.3 m, r_2=0.25 m, r_3=0.05m
m_1=2.16 kg, m_2=1.2 kg, m_3=0.48 kg
I_1=0.01755 kgm², I_2=0.0067 kgm², I_3=0.00028 kgm²

$$\dot z_{2i}=-r_1b_iS_2\dot q_2/z_{2i} \quad (12)$$
$$\ddot z_{2i}=-r_1b_i[C_2+r_1b_i(S_2\dot q_2/z_{2i})^2+S_2\ddot q_2] \quad (13)$$
$$F_{2i}=(r_1^2+b_i^2+2r_1b_iC_2)^{1/2}T_2/(r_1b_iS_2) \quad (14)$$

where z_{2i}, $\dot z_{2i}$, $\ddot z_{2i}$ and F_{2i} are the length, velocity, acceleration and force on the biceps brachii (i=1) and triceps brachii (i=2). Moreover, according to the biological data, we consider the upper (q_{2MAX}) and lower (q_{2MIN}) limits of the range of motion of the elbow joint to be:

$$q_{2MAX}=\pi,\ q_{2MIN}=0 \quad (15)$$

Expressions (1)-(5) together with expressions (11)-(14) indicate that we may describe the robotic arm in the "muscle-space" alternatively to the standard operational and joint spaces. Moreover, formula (12) reveals that the $1/S_2$ degrading factor, that affects $\dot q_2$ in:

$$\dot q=\theta(p,\dot p) \quad (16)$$

is now compensated. Therefore, we conclude that the shoulder and elbow structures have different anatomic-levers that adapt the operational exigencies to the muscle requirements.

Table 1 depicts average data [5-6] that will be used in the sequel. One should note that this data may vary significantly; nevertheless, after performing several experiments, we concluded that numerical variations have a minor influence on the statistical analysis presented in the sequel.

On the Statistical Study of Muscle-Actuated Arms

In this section we study, statistically, both the kinematics and kinematics + dynamics of the muscle-actuated arm. As mentioned before (8)-(15), we consider the following range of motion for the two joints:

$$-5\pi/6\le q_1\le\pi/6,\ 0\le q_2\le\pi \quad (17)$$

The human arm can reach a larger area in the sagittal plane. In fact, q_1 has an upper limit of $\pi/2$ or beyond due to the rotation of the spinal column through action of the lumbar muscles. These muscles rotate the T-structure and the arm as a whole and therefore, have a minor effect on the requirements posed to the muscles considered in this article.

Figures 4 and 5 show typical charts of the 95% inter-percentile range (i.e. the difference between the 97.5% and 2.5% percentiles) for the anterior/posterior deltoids (shoulder) and the biceps/triceps brachii (elbow). In these numerical experiments we used probability density functions (p.d.f.'s) for position, velocity and acceleration

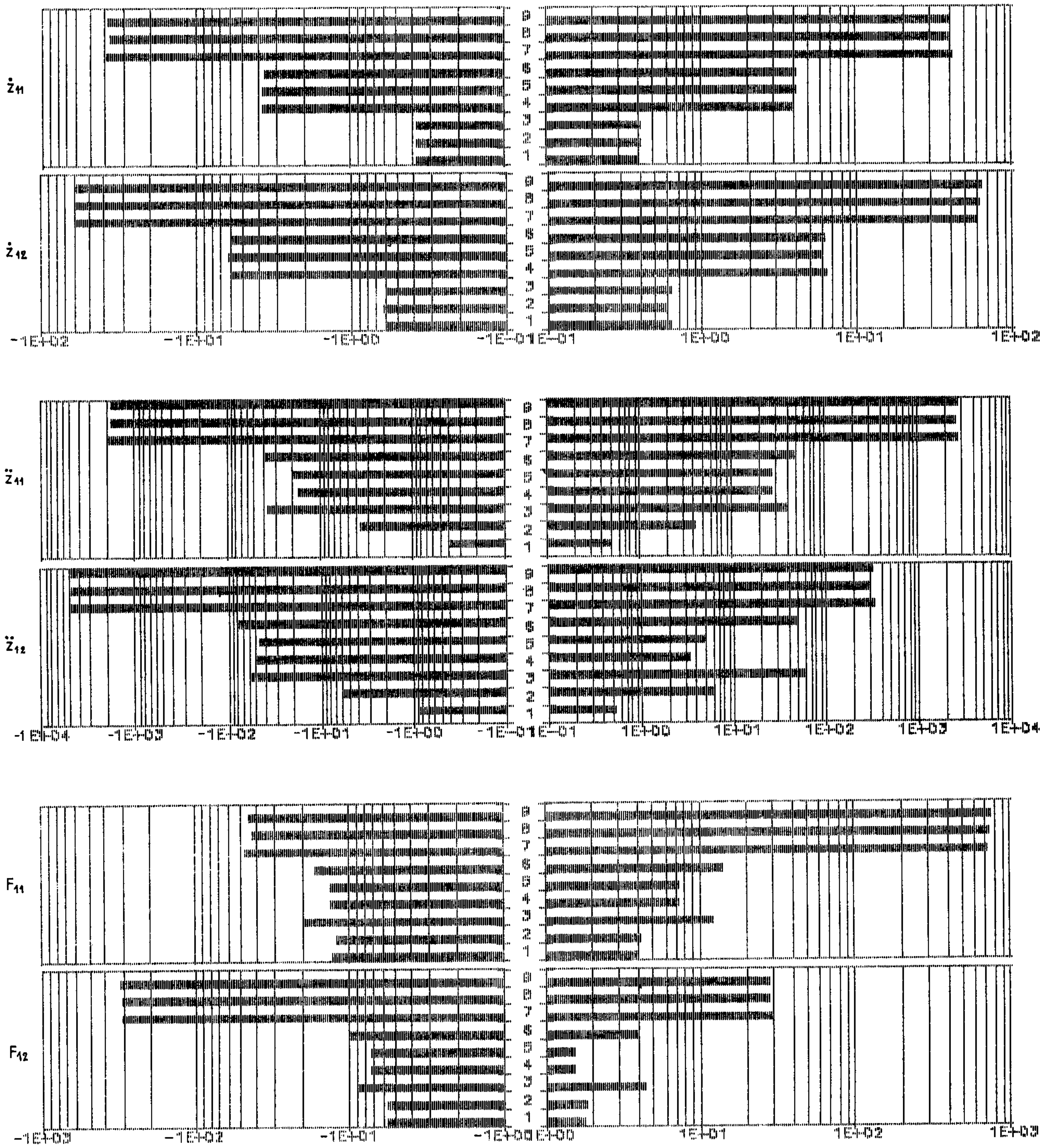

Fig. 4 Comparison charts of the kinematic and dynamic performances for the anterior and posterior deltoids when "excited" with p.d.f.'s (18)-(20), for the nine categories under study.
$\{\dot{z}_{11}, \ddot{z}_{11}, F_{11}\}$: velocity, acceleration and force on the anterior deltoid
$\{\dot{z}_{12}, \ddot{z}_{12}, F_{12}\}$: velocity, acceleration and force on the posterior deltoid

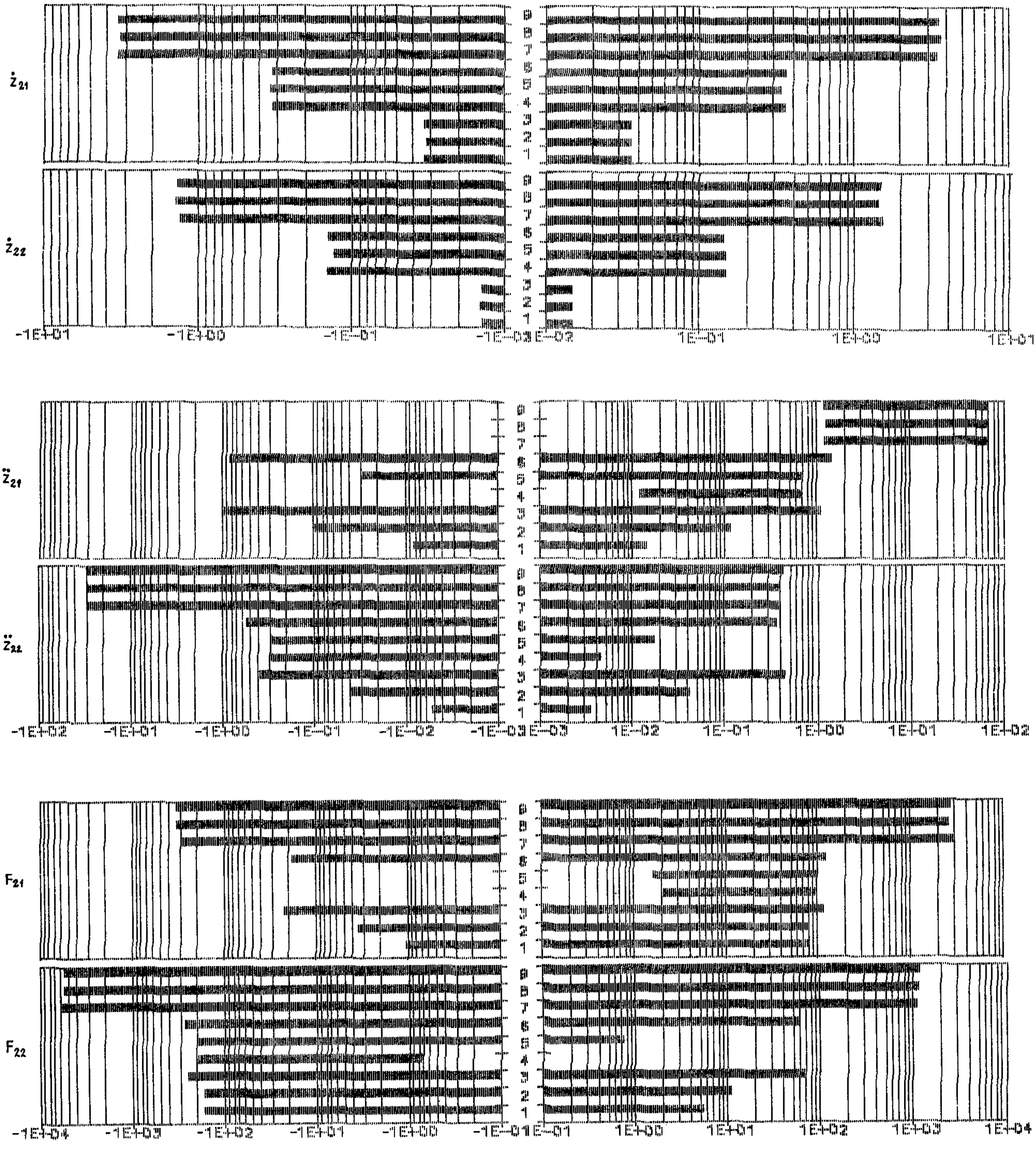

Fig. 5 Comparison charts of the kinematic and dynamic performances for the biceps brachii and triceps brachii when "excited" with p.d.f.'s (18)-(20), for the nine categories under study.
$\{\dot{z}_{21}, \ddot{z}_{21}, F_{21}\}$: velocity, acceleration and force on the biceps brachii
$\{\dot{z}_{22}, \ddot{z}_{22}, F_{22}\}$: velocity, acceleration and force on the triceps brachii

of the type [1,2] ($p=[x,y]^T$):

$$f_Q(q_1,q_2)=\text{constant}*(S_1S_2)^3 \quad (18)$$

$$f_P(\dot{p},q_2)=\text{EXP}\{-(\dot{x}^2+\dot{y}^2)/[2\sigma_{\dot{P}}^2(q_2)]\}/[2\pi\sigma_{\dot{P}}^2(q_2)] \quad (19a)$$

$$\sigma_P(q_2)=\begin{cases}2\sigma_{\dot{P}}|q_2|/\pi & \text{if } 0<|q_2|\leq\pi/2\\ 2\sigma_{\dot{P}}|q_2-\pi|/\pi & \text{if } \pi/2<|q_2|\leq\pi\end{cases} \quad (19b)$$

$$f_P(\ddot{p},q_2)=\text{EXP}[-(\ddot{x}^2+\ddot{y}^2)/[2\sigma_{\ddot{P}}^2(q_2)]\}/[2\pi\sigma_{\ddot{P}}^2(q_2)] \quad (20a)$$

$$\sigma_P(q_2)=\begin{cases}2\sigma_{\ddot{P}}|q_2|/\pi & \text{if } 0<|q_2|\leq\pi/2\\ 2\sigma_{\ddot{P}}|q_2-\pi|/\pi & \text{if } \pi/2<|q_2|\leq\pi\end{cases} \quad (20b)$$

and operational requirements of velocity and acceleration corresponding to the nine categories:

1. $\sigma_{\dot{P}}=0.1$ $\sigma_{\ddot{P}}=0.1$ 4. $\sigma_{\dot{P}}=1$ $\sigma_{\ddot{P}}=0.1$ 7. $\sigma_{\dot{P}}=10$ $\sigma_{\ddot{P}}=0.1$
2. $\sigma_{\dot{P}}=0.1$ $\sigma_{\ddot{P}}=1$ 5. $\sigma_{\dot{P}}=1$ $\sigma_{\ddot{P}}=1$ 8. $\sigma_{\dot{P}}=10$ $\sigma_{\ddot{P}}=1$
3. $\sigma_{\dot{P}}=0.1$ $\sigma_{\ddot{P}}=10$ 6. $\sigma_{\dot{P}}=1$ $\sigma_{\ddot{P}}=10$ 9. $\sigma_{\dot{P}}=10$ $\sigma_{\ddot{P}}=10$

We conclude that:

• As expected due to (12), high velocity requirements are more stringent for the shoulder than for the elbow. Therefore, high speed movements in muscle-actuated arms must privilege trajectories having low $\dot{q}_1$ and high $\dot{q}_2$.

• Positive and negative exigencies in the muscle-actuated structure tend to distribute "orderly" to each muscle of antagonist joint-actuating pair. By other words, histograms are, predominantly, positive (negative) for the flexion (extension) muscle. This observation confirms that our statistical approach is, indeed, consistent with the way biological muscles work.

• The muscle forces are dominated by gravitational effects for low and medium velocity requirements. For high velocities forces become higher.

• Acceleration requirements have a small effect upon the muscle forces.

These observations are in close agreement with those obtained for the joint-actuated manipulators [1] namely that we are dealing with "position and acceleration" machines. Furthermore, we can also conclude that the "amplification" between operational exigencies and actuator requirements is much higher for joint-actuated manipulators than for muscle-actuated arms. In fact, biological arms have superior performances because muscle-actuated anatomic-levers adapt the operation requirements in contrast with joint-actuated machines where actuators have to fully support those exigencies.

Conclusions

A statistical approach to the analysis of biomechanical manipulators was presented. The new method stems from previous studies on mechanical joint-actuated manipulators. Motivated by the kinesiological aspects of the human arm we demonstrate that biomechanical structures have better performances than standard manipulators. In fact, joint-actuated robotic structures are non-optimal because they have to support the direct impact of the operational requirements. On the other hand, muscle-actuated arms are, intrinsically, superior because the anatomic-levers adapt the operational exigencies to the actuators. This observation is of utmost importance as it gives a clear basis to the design of new mechanical manipulator structures, with performances close to the biological systems.

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