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On the Analysis of Muscle-Actuated Manipulators

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Abstract

In previous studies a statistical method for the analysis and design of robot manipulators was developed. 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. Therefore, the results are a step towards the design of new mechanical robotic structures, with performances close to the biological systems.

1. Introduction

Human activities adopt anthropomorphic concepts which require tools and processes according to these principles. In this sense, a robot manipulator is a tool that extends the human capabilities having the arm as its reference concept. However, this observation is confronted with the present day situation where robot technology makes an insignificant appeal to the biological aspects of the human arm. This paper analyses the performances of biomechanical-like arms and is organized as follows. Section two addresses the kinesiology of the arm and formulates the corresponding engineering models. Section three presents a statistical analysis of the new manipulating system which demonstrates the superior performances of these structures. Finally, in section four conclusions are drawn.

2. An Engineering Model for Muscle-Actuated Arms

Mechanical manipulators are described through the kinematic and dynamic models. These models relate positions, velocities, accelerations and forces/torques on the operational $\{p, \dot{p}, \ddot{p}, \Gamma\}$ and joint $\{q, \dot{q}, \ddot{q}, T\}$ spaces. For a n degrees of freedom manipulator each joint torque has an intricate relationship with the other variables. Therefore, clear and systematic guidelines towards the implementation of optimal manipulating structures are still lacking. The authors developed a statistical method [1,2] which demonstrates that, for tasks in the operational space, mechanical joint-actuated manipulators are much more sensitive to velocity than to acceleration requirements. Moreover, the results point out that the standard robot actuators are not well adapted to the transients imposed by the robotic applications. Alternative solutions based on muscle-like actuators [3-6], with appropriate mechanical levers, allow more efficient manipulating structures. Having these ideas in mind, in this section we address the kinesiological aspects of the human arm and we design a simplified engineering system that mimics its main characteristics.

The human arm may be considered as the optimal manipulator and, therefore, it constitutes an adequate reference system for the study and development of the new concepts. Extensive biological studies [7-10] have been carried out on this subject, unfortunately precise conclusions on all of the phenomena involved 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. Furthermore, in order to simplify matters, only the motion in the sagittal plane will be considered on the analysis of the shoulder (sub-section 2.1) and elbow (sub-section 2.2) structures [11,12].

2.1. The Shoulder

Kinesiological studies show that the movement of the shoulder structure involves a multitude of muscles which are distributed through the sternoclavicular, acromioclavicular and glenohumeral structures. This anatomic arrangement leads to the reduction on the exigencies posed to the muscles, the extensive freedom of motion enjoyed by the upper arm and the existence of anatomic-levers which adapt the operational tasks to the muscle requirements.

Figure 1 represents a simplified engineering model, in the sagittal plane, of this anatomic mechanism. 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} or q_{02}) of the arm movement (q_1). By other words, 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 have for the anterior (i=1) and posterior (i=2) deltoids lengths (z_{1i}), velocities ($\dot{z}_{1i}$), accelerations ($\ddot{z}_{1i}$), and forces (F_{1i}) given by the expressions:

i) For the anterior deltoid when wound up in the pulley ($-2\pi/3 \le q_1 \le -\pi/18$)

$$z_{11} = h\{q_{01} - \mathrm{ASIN}[1-(h/d)^2]^{1/2}\} + (d^2-h^2)^{1/2} \quad (1a)$$

$$\dot{z}_{11} = h\dot{q}_{01} \quad (1b)$$

$$\ddot{z}_{11} = h\ddot{q}_{01} \quad (1c)$$

$$F_{11} = T_1/h \quad (1d)$$

ii) For the anterior deltoid when acting freely ($-\pi/18 \le q_1 \le 4\pi/9$)

$$z_{11} = (d^2+h^2-2dhC_{01})^{1/2} \quad (2a)$$

$$\dot{z}_{11} = (dhS_{01}/z_{11})\dot{q}_{01} \quad (2b)$$

$$\ddot{z}_{11} = (dh/z_{11})[(z_{11}{}^2C_{01} - dhS_{01}{}^2)(\dot{q}_{01}/z_{11})^2 + S_{01}\ddot{q}_{01}] \quad (2c)$$

$$F_{11} = T_1 z_{11}/(dhS_{01}) \quad (2d)$$

iii) For the posterior deltoid, which wound up in the pulley throughout the range of the arm mouvement ($-2\pi/3 \le q_1 \le 4\pi/9$)

$$z_{12} = h\{2\pi - q_{02} - \mathrm{ASIN}[1-(h/d)^2]^{1/2}\} + (d^2-h^2)^{1/2} \quad (3a)$$

$$\dot{z}_{12} = -h\dot{q}_{02} \quad (3b)$$

$$\ddot{z}_{12} = -h\ddot{q}_{02} \quad (3c)$$

$$F_{12} = -T_1/h \quad (3d)$$

where h and d are parameters of the pulley (Table 1).

The kinematic control scheme of the shoulder that is, the relationship between the position of the humerus and the position of the pulley is assumed to obey the following equations which are in accordance with the available biological data:

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

$$q_{02} = \begin{cases} 1.083\pi - 0.5q_1 & -2\pi/3 \le q_1 \le -\pi/2 \\ 0.833\pi - q_1 & -\pi/2 < q_1 \le -\pi/6 \\ 0.917\pi - 0.5q_1 & -\pi/6 < q_1 \le \pi/6 \\ 0.75\pi + 0.5q_1 & \pi/6 < q_1 \le 4\pi/9 \end{cases} \quad (5)$$

These equations represent a compromise between the minimization of the the deltoid requirements and the pulley actuator requirements.

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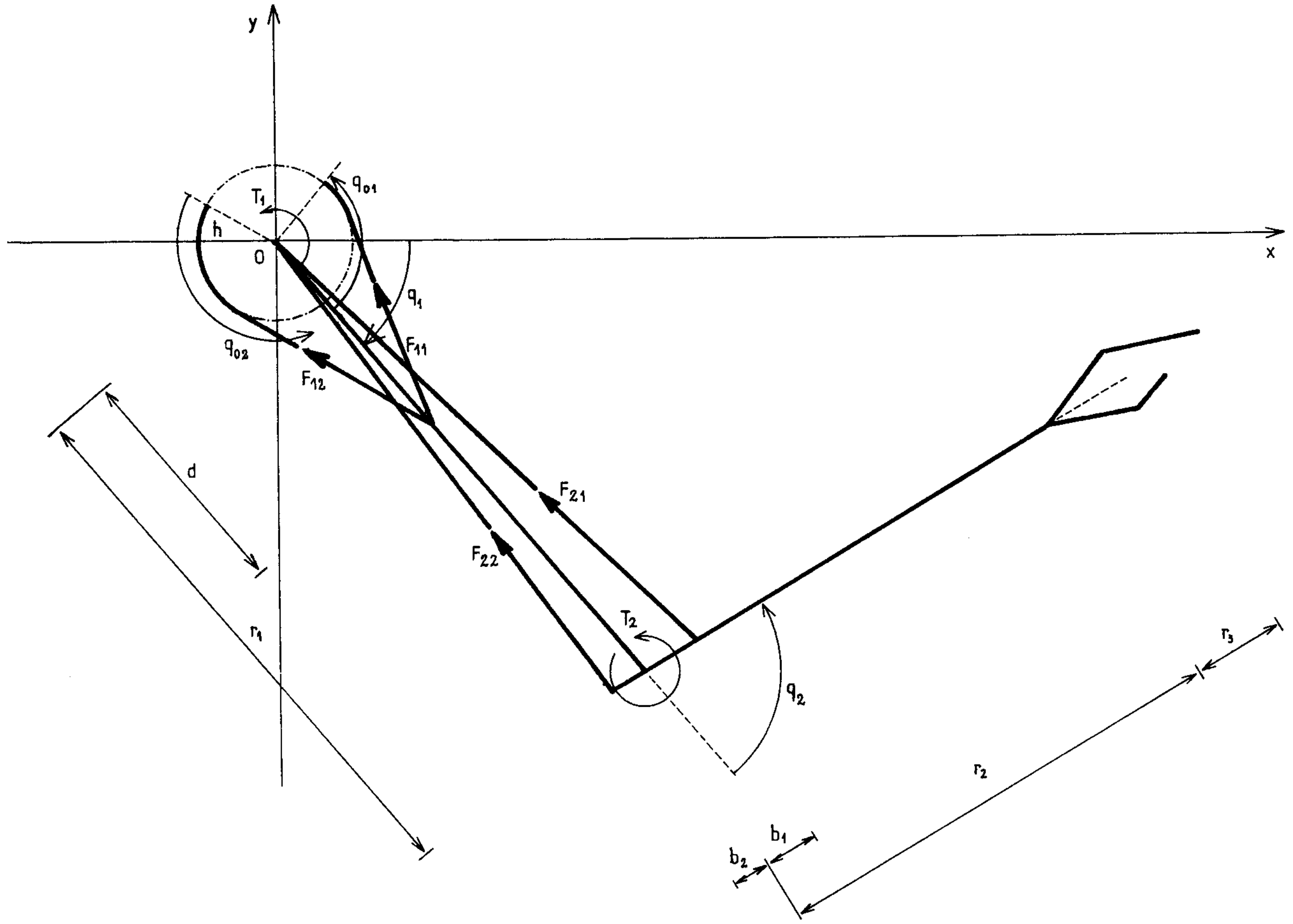

Fig. 1 Engineering model of the human arm in the sagittal plane for the shoulder and the elbow structures.

2.2. The Elbow Structure

The elbow movement in the sagittal plane (q_2) requires also several muscles. Considering only the biceps brachii and the triceps brachii, because they are the more influential, we can design a simplified engineering system as the one shown in Figure 1. For this structure we have (i=1,2):

$$z_{2i}=(r_1{}^2+b_i{}^2+2r_1b_iC_2)^{1/2} \quad (6a)$$
$$\dot{z}_{2i}=-r_1b_iS_2\dot{q}_2/z_{2i} \quad (6b)$$
$$\ddot{z}_{2i}=-r_1b_i[C_2+r_1b_i(S_2\dot{q}_2/z_{2i})^2+S_2\ddot{q}_2] \quad (6c)$$
$$F_{2i}=(r_1{}^2+b_i{}^2+2r_1b_iC_2)^{1/2}T_2/(r_1b_iS_2) \quad (6d)$$

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) and b_i is a parameter (Table 1). Moreover, according to the biological data, we consider the range of motion of the elbow joint to be:

$$0\le q_2\le\pi \quad (7)$$

Formula (6b) reveals that the $S_2{}^{-1}$ degrading factor, that affects $\dot{q}_2$ in the kinematic transformation $\dot{q}_2=\theta(p,\dot{p})$ is now compensated. Moreover, we can conclude that the shoulder and elbow structures have different anatomic-levers that adapt the operational exigencies to the muscle requirements.

Table 1 Numerical parameters of the arm.

d=0.126 m, h=0.043 m, b_1=0.034 m, b_2=-0.02 m
r_1=0.3 m, r_2=0.25 m, r_3=0.05 m
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

3. The Statistical Analysis of Muscle-Actuated Arms

In this section we analyse, statistically, the kinematic and dynamic performances of muscle-actuated arms. Figures 2 and 3 show typical charts of the 95% inter-percentile range for the anterior/posterior deltoids (shoulder) and the biceps/triceps brachii (elbow). In these numerical experiments we use probability density functions (p.d.f.'s) for position, velocity and acceleration of the type ($p=[x,y]^T$, $q=[q_1,q_2]^T$):

$$f_Q(q_1)=\begin{cases}1.094q_1+2.292 & -2\pi/3\le q_1\le-\pi/2\\ -0.193q_1+0.27 & -\pi/2<q_1\le4\pi/9\end{cases} \quad (8a)$$
$$f_Q(q_2)=\text{constant}*|S_2|^3 \qquad 0\le q_2\le\pi \quad (8b)$$

$$f_{\dot{P}}(\dot{p},q_2)=\text{EXP}\{-(\dot{x}^2+\dot{y}^2)/[2\sigma_{\dot{P}}{}^2(q_2)]\}/[2\pi\sigma_{\dot{P}}{}^2(q_2)] \quad (9a)$$

$$\sigma_{\dot{P}}(q_2)=\begin{cases}2\sigma_{\dot{P}}|q_2|/\pi & \text{if } 0\le|q_2|\le\pi/2\\ 2\sigma_{\dot{P}}|q_2-\pi|/\pi & \text{if } \pi/2<|q_2|\le\pi\end{cases} \quad (9b)$$

$$f_{\ddot{P}}(\ddot{p},q_2)=\text{EXP}[-(\ddot{x}^2+\ddot{y}^2)/[2\sigma_{\ddot{P}}{}^2(q_2)]\}/[2\pi\sigma_{\ddot{P}}{}^2(q_2)] \quad (10a)$$

$$\sigma_{\ddot{P}}(q_2)=\begin{cases}2\sigma_{\ddot{P}}|q_2|/\pi & \text{if } 0\le|q_2|\le\pi/2\\ 2\sigma_{\ddot{P}}|q_2-\pi|/\pi & \text{if } \pi/2<|q_2|\le\pi\end{cases} \quad (10b)$$

and operational requirements of $\dot{p}$ and $\ddot{p}$ corresponding to the nine categories of standard deviation in p.d.f.'s (9)-(10):

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

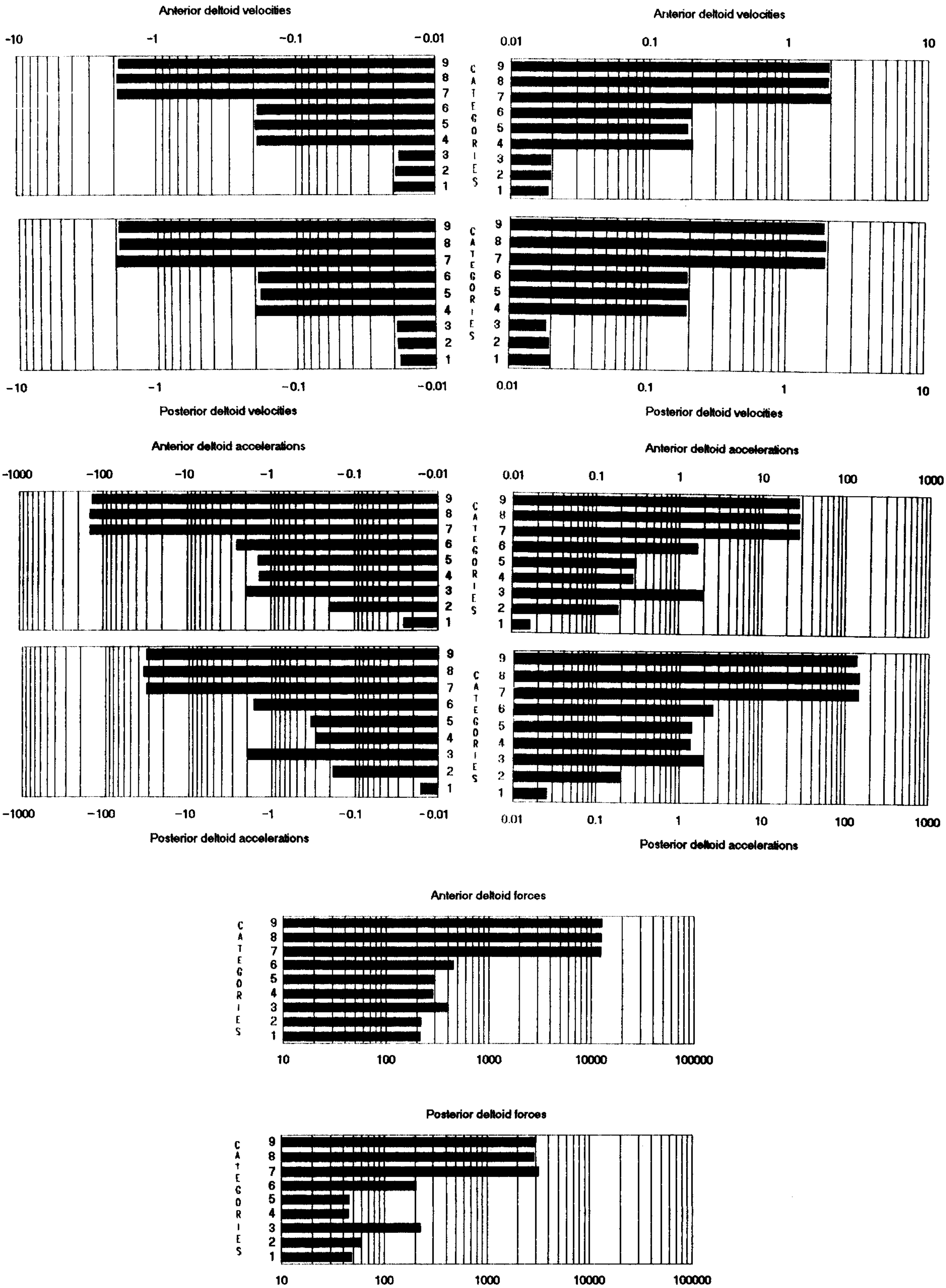

Fig. 2 Comparison charts of the performances for the anterior and posterior deltoids when "excited" with p.d.f.'s (8)-(10), for the nine categories of velocity and acceleration under study.

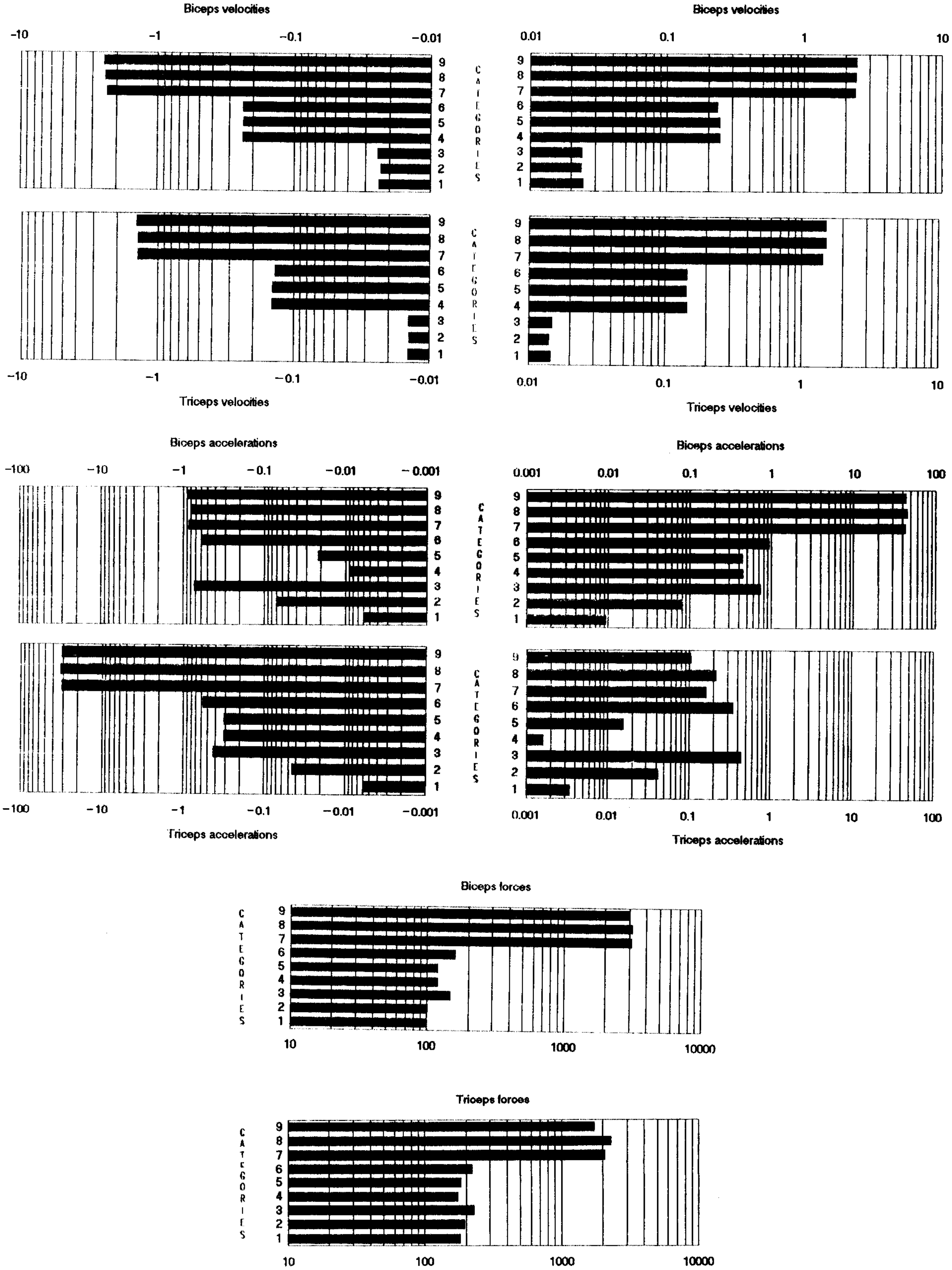

Fig. 3 Comparison charts of the kinematic and dynamic performances for the biceps brachii and triceps brachii when "excited" with p.d.f.'s (8)-(10), for the nine categories of velocity and acceleration under study.