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ON THE STATISTICAL ANALYSIS OF BIOMECHANICAL ARMS

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Abstract. Standard joint-actuated manipulators have poor performances due to the high requirements imposed by the transients of the operational tasks. Muscle-actuated arms are superior because the anatomic levers adapt the manipulating requirements to the actuators. The statistical analysis of these systems highlights its main properties and constitutes a step towards the design of new mechanical robotic structures, with performances closer to the biological arms.

Keywords. Manipulators, modelling, robots, robotics, statistics.

INTRODUCTION

The poor performances of industrial manipulators, when compared with the human arm, motivated the development of better mechanical structures. Research in this area led to the implementation of direct drive mechanical arms (Asada and Youcef-Toumi, 1984), the study of lightweight flexible manipulators (Rovner and Cannon Jr., 1987) and the development of mathematical and computer models of the kinematic and dynamic phenomena (Tsai and Soni, 1981; Yoshikawa, 1986). However, clear guidelines towards the implementation of optimal manipulating structures are still lacking. The authors developed a statistical method which demonstrates that, for tasks defined 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 actuators are not well adapted to the transients imposed by the robotic applications. In fact, alternative solutions, based on muscle-like actuators, with appropriate mechanical levers, allow more efficient manipulating structures. This paper analyses biomechanical-like arms and is organized as follows. Section two addresses the kinesiological aspects of the human arm and formulates the corresponding geometrical models. Section three presents the performances of biomechanical-like (i.e. muscle-driven) manipulators. Finally, in section four conclusions are drawn.

A GEOMETRIC MODEL 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 $\{p, dp/dt, d^2p/dt^2, \Gamma\}$ and joint $\{q, dq/dt, d^2q/dt^2, T\}$ spaces. However, even for simple manipulators the joint torques reveal complex relationships with the other variables. Due to this reason, there are not yet systematic algorithms towards the implementation of optimal structures. The statistical modelling of robot manipulators (Galhano, Machado and de Carvalho, 1990a, 1991b) demonstrates that joint-actuated manipulators are much more sensitive to dp/dt than to d^2p/dt^2 and moreover, that standard robot actuators are not well adapted to the transients imposed by robotic applications. Therefore, alternative solutions based on muscle-like actuators (De Rossi, Domenici and Chiarelli, 1986; Kuribayashi, 1986; Tatara, 1987; Caldwell and Taylor, 1988), 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 geometrical model that reflects its main properties. Extensive studies (Ito and co-workers, 1979; An and co-workers, 1981; Kapandji, 1983; Akazawa and Fujii, 1986) have been carried out on the analysis of the human arm, unfortunately there are not precise conclusions on this subject. Therefore, in order to simplify matters, only the motion in the sagittal plane will be considered on the analysis of the shoulder and elbow structures (Galhano, Machado and de Carvalho, 1990b, 1991a).

The Shoulder Structure

The movement of the shoulder involves a multitude of muscles which are distributed through the sternoclavicular, acromioclavicular and glenohumeral structures. This

kinesiological arrangement leads to the reduction on the exigencies posed to the muscles, through the implementation of anatomic levers which adapt the operational tasks to the muscle requirements. Figure 1 represents 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). 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. In this structure we have for the anterior ($i=1$) and posterior ($i=2$) deltoids range of motion, lengths (z_{1i}), velocities (dz_{1i}/dt), accelerations (d^2z_{1i}/dt^2), and forces (F_{1i}) given by the expressions:

A.1. For the anterior deltoid when wound up in the pulley

$$-\frac{2\pi}{3} \leq q_1 < -\frac{\pi}{18} \quad (1a)$$

$$z_{11} = h \left[q_{01} - \text{asin} \left(\frac{\sqrt{d^2 - h^2}}{d} \right) \right] + \sqrt{d^2 - h^2} \quad (1b)$$

$$\frac{dz_{11}}{dt} = h \frac{dq_{01}}{dt} \quad (1c)$$

$$\frac{d^2z_{11}}{dt^2} = h \frac{d^2q_{01}}{dt^2} \quad (1d)$$

$$F_{11} = \frac{T_1}{h} \quad (1e)$$

A.2. For the anterior deltoid when acting freely

$$-\frac{\pi}{18} \leq q_1 \leq \frac{4\pi}{9} \quad (2a)$$

$$z_{11} = \sqrt{d^2 + h^2 - 2dhC_{01}} \quad (2b)$$

$$\frac{dz_{11}}{dt} = \left(\frac{dhS_{01}}{z_{11}} \right) \frac{dq_{01}}{dt} \quad (2c)$$

$$\frac{d^2z_{11}}{dt^2} = \frac{dh}{z_{11}} \left[\left(\frac{z_{11}^2 C_{01} - dhS_{01}^2}{z_{11}^2} \right) \left(\frac{dq_{01}}{dt} \right)^2 + S_{01} \frac{d^2q_{01}}{dt^2} \right] \quad (2d)$$

$$F_{11} = \left(\frac{z_{11}}{dhS_{01}} \right) T_1 \quad (2e)$$

B. For the posterior deltoid, which wound up in the pulley throughout the range of the arm movement

$$\frac{-2\pi}{3} \leq q_1 \leq \frac{4\pi}{9} \quad (3a)$$

$$z_{12} = h \left[2\pi - q_{02} - \text{asin} \left(\frac{\sqrt{d^2 - h^2}}{d} \right) \right] + \sqrt{d^2 - h^2} \quad (3b)$$

$$\frac{dz_{12}}{dt} = -h \frac{dq_{02}}{dt} \quad (3c)$$

$$\frac{d^2z_{12}}{dt^2} = -h \frac{d^2q_{02}}{dt^2} \quad (3d)$$

$$F_{12} = -\frac{T_1}{h} \quad (3e)$$

where h and d are geometrical parameters (Table 1).

TABLE 1 Parameters of the Muscle-Actuated Manipulator.

$d=0.126$ 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
$I_1=0.01755$ kgm ²	$I_2=0.0067$ kgm ²	$I_3=0.00028$ kgm ²

On the other hand, 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 equations:

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

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

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

The Elbow Structure

The movement of the elbow 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 the geometrical model depicted in Fig. 1. For this system we have for the biceps brachii ($i=1$) and triceps brachii ($i=2$) range of motion, lengths (z_{2i}), velocities (dz_{2i}/dt), accelerations (d^2z_{2i}/dt^2), and forces (F_{2i}) given by the expressions:

$$0 \leq q_2 \leq \pi \quad (5a)$$

$$z_{2i} = \sqrt{r_1^2 + b_1^2 + 2r_1 b_1 C_2} \quad (5b)$$

$$\frac{dz_{2i}}{dt} = - \left(\frac{r_1 b_1 S_2}{z_{2i}} \right) \frac{dq_2}{dt} \quad (5c)$$

$$\frac{d^2z_{2i}}{dt^2} = - \frac{r_1 b_1}{z_{2i}} \left\{ \left[C_2 + r_1 b_1 \left(\frac{S_2}{z_{2i}} \right)^2 \right] \left(\frac{dq_2}{dt} \right)^2 + S_2 \frac{d^2q_2}{dt^2} \right\} \quad (5d)$$

$$F_{2i} = \left(\frac{\sqrt{r_1^2 + b_1^2 + 2r_1 b_1 C_2}}{r_1 b_1 S_2} \right) T_2 \quad (5e)$$

where b_1 is a parameter (Table 1).

Expression (5c) reveals that the S_2^{-1} (degrading) factor, that affects the inverse kinematic transformation of joint-actuated robots 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.

THE STATISTICAL ANALYSIS OF MUSCLE-ACTUATED ARMS

In this section we analyse, statistically, the kinematic and dynamic performances of muscle-actuated arms. Contrary to other studies we are not concerned to the modelling of the muscles but, in fact, we describe the task requirements and the manipulator structure. 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 a numerical sample obeying the following probability density functions (p.d.f.'s) for position (with $K=3$), velocity and acceleration ($p=[p_1, p_2]^T$, $q=[q_1, q_2]^T$):

$$g_p(q_1) = \begin{cases} 1.094q_1 + 2.292 & \text{if } -2\pi/3 \leq q_1 \leq \pi/2 \\ -0.193q_1 + 0.27 & \text{if } -\pi/2 < q_1 \leq 4\pi/9 \end{cases} \quad (6a)$$

$$g_p(q_2) = \chi * |S_2|^K \quad \text{for} \quad 0 \leq q_2 \leq \pi \quad (6b)$$

$$\chi = \begin{cases} \frac{1}{2\pi} & \text{if } K = 0 \\ \frac{1}{4} & \text{if } K = 1 \\ \frac{2 \cdot 4 \cdot 6 \dots K}{1 \cdot 3 \cdot 5 \dots K-1} \cdot \frac{1}{2\pi} & \text{if } K = 2; 4; 6 \dots \\ \frac{1 \cdot 3 \cdot 5 \cdot 7 \dots K}{2 \cdot 4 \cdot 6 \dots K-1} \cdot \frac{1}{4} & \text{if } K = 3; 5; 7 \dots \end{cases} \quad (6c)$$

$$f_v(dp/dt) = \frac{1}{2\pi\sigma_v^2} \text{EXP} \left\{ -\frac{(dp_1/dt)^2 + (dp_2/dt)^2}{2\sigma_v^2} \right\} \quad (7)$$

$$f_A(d^2p/dt^2) = \frac{1}{2\pi\sigma_A^2} \text{EXP} \left\{ -\frac{(d^2p_1/dt^2)^2 + (d^2p_2/dt^2)^2}{2\sigma_A^2} \right\} \quad (8)$$

In p.d.f.'s (7) and (8) we consider the nine categories of operational requirements of dp/dt and d^2p/dt^2 presented in Table 2. Such p.d.f.'s were proposed in previous studies (Galhano, Machado and de Carvalho, 1990a, 1991b) and characterize, statistically, a class of kinematic and dynamic requirements posed to the manipulator. Figures 2 and 3 show the requirements posed to the anterior/posterior deltoids (shoulder) and the biceps/triceps brachii (elbow), respectively. One should note that, in the charts, our performance index has a different calculation procedure according to the variables:

- Because velocities and accelerations at the muscles can be both positive and negative, the index corresponds to the difference between the 97.5th and 2.5th percentiles of the histograms.
- Because muscles are unidirectional actuators (i.e. muscles do not develop negative forces) the index corresponds to the 95% of the positive part of the histograms.

The numerical value of 95% can be interpreted as the "greater part of the cases", nevertheless, experiments demonstrated that alternative values lead to similar conclusions. The results show that:

- The muscle forces are dominated by gravitational effects for low and medium velocity requirements.
- For high velocities the required forces become much higher.
- Acceleration requirements have a much smaller effect upon the muscle forces than velocity requirements.

These observations are in close agreement with those obtained for the joint-actuated manipulators, namely that, in a statistical sense,

TABLE 2 Categories of Operational Requirements

Categories	σ_v	σ_A
1	0.1	0.1
2	0.1	1
3	0.1	10
4	1	0.1
5	1	1
6	1	10
7	10	0.1
8	10	1
9	10	10

we are dealing with machines much more sensitive to dp/dt than to d^2p/dt^2 . Furthermore, the "amplification" between exigencies in the operational space and actuator requirements is much higher for joint-actuated manipulators than for muscle-actuated arms. An increase in the requirements on the operational space (i.e. an increase in σ_v and σ_A) produces a similar result both on the joint and muscle actuators; nevertheless, the amplification factors for the kinematic transformations $\{p, dp/dt, d^2p/dt^2, \Gamma\} \rightarrow \{q, dq/dt, d^2q/dt^2, T\}$ and $\{p, dp/dt, d^2p/dt^2, \Gamma\} \rightarrow \{z, dz/dt, d^2z/dt^2, F\}$ are of different magnitudes because the mechanical levers scale down the factor in the second case.

In this line of thought the authors are developing an electromagnetic linear actuator for manipulators. This actuator consists on a set of "small cells" in series, so that the load displacement corresponds to the sum of the components driven by each cell.

CONCLUSIONS

The statistical analysis of biomechanical manipulators was presented. The new approach stems from companion studies on the properties of 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, while muscle-actuated arms are superior because they have anatomic levers which adapt the operational exigencies to the actuators. Therefore, these results are a step towards the design of a new generation of better mechanical manipulators.

REFERENCES

Akazawa, K. and K. Fujii (1986). Theory of Muscle Contraction and Motor Control. *Advanced Robotics*, 1, 379-390.
 An, K.N., F.C. Hui, B.F. Morrey, R.L. Linscheid and E.Y. Chao (1981). Muscles Across the Elbow Joint: A Biomechanical Analysis. *J. of Biomechanics*, 14, 659-669.
 Asada, H. and K. Youcef-Toumi (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.

- Caldwell, D.G. and P.M. Taylor (1988). Artificial Muscles as Robotic Actuators. IFAC Symp. on Robot Control SYROCO'88, Karlsruhe, FRG, 40.1-40.6.
- De Rossi, D., C. Domenici and P. Chiarelli (1986). Analogs of Biological Tissues for Mechano-electrical Transduction: Tactile Sensors and Muscle-Like Actuators. NATO ARW on Sensors and Sensory Systems for Advanced Robots, Maratea, Italy.
- Galhano, A.M.S.F., J.A.T. Machado and J.L.M. de Carvalho (1990). On the Analysis and Design of Robot Manipulators: A Statistical Approach. 11th IFAC World Congress, Tallinn, USSR., 249-254.
- Galhano, A.M.S.F., J.A.T. Machado and J.L.M. de Carvalho (1990). On the Analysis and Design of Robot Manipulators: A Statistical Perspective. IEEE Int. Workshop on Advanced Motion Control, Yokohama, Japan.,
- Galhano, A.M.S.F., J.A.T. Machado and J.L.M. de Carvalho (1991). On the Analysis of Muscle-Actuated Manipulators. Fifth Int. Conf. on Advanced Robotics, Pisa, Italy.
- Galhano, A.M.S.F., J.A.T. Machado and J.L.M. de Carvalho (1991). On The Statistical Modelling of Mechanical Manipulators. IFAC Symposium on Robot Control SYROCO'91, Vienna, Austria.
- Ito, N., R. Suzuki, K. Ishimura and H. Kuwahara (1979). Electromyographic Study of Shoulder Joint. 4th Congress of I.S.E.K., Boston, USA, 22-23.
- Kapandji, I. (1983). In Maloine S. A. (Ed.), *Physiologie Articulaires - Schémas Commentés de Mécanique Humaine - Tome 1, Membre Supérieur*.
- Kuribayashi, K. (1986). A New Actuator of a Joint Mechanism Using TiNi Alloy Wire. *The Int. J. Robotics Research*, 4, 47-58.
- Rovner, D.M. and R.H. Cannon Jr. (1987). Experiments Toward On-Line Identification and Control of a Very Flexible One-Link Manipulator. *The Int. J. Robotics Research*, 6., 3-19.
- Tatara, Y. (1987). Mechanochemical Actuators. *Advanced Robotics*, 2, 69-85.
- Tsai, Y.C. and A.H. Soni (1981). Accessible Region and Synthesis of Robot Arms. *ASME J. Mechanical Design*, 103, 803-811.
- Yoshikawa, T. (1986). Analysis and Design of Articulated Robot Arms from the Viewpoint of Dynamic Manipulability. Robotics Research, The Third Int. Symp., MIT Press, 273-279.

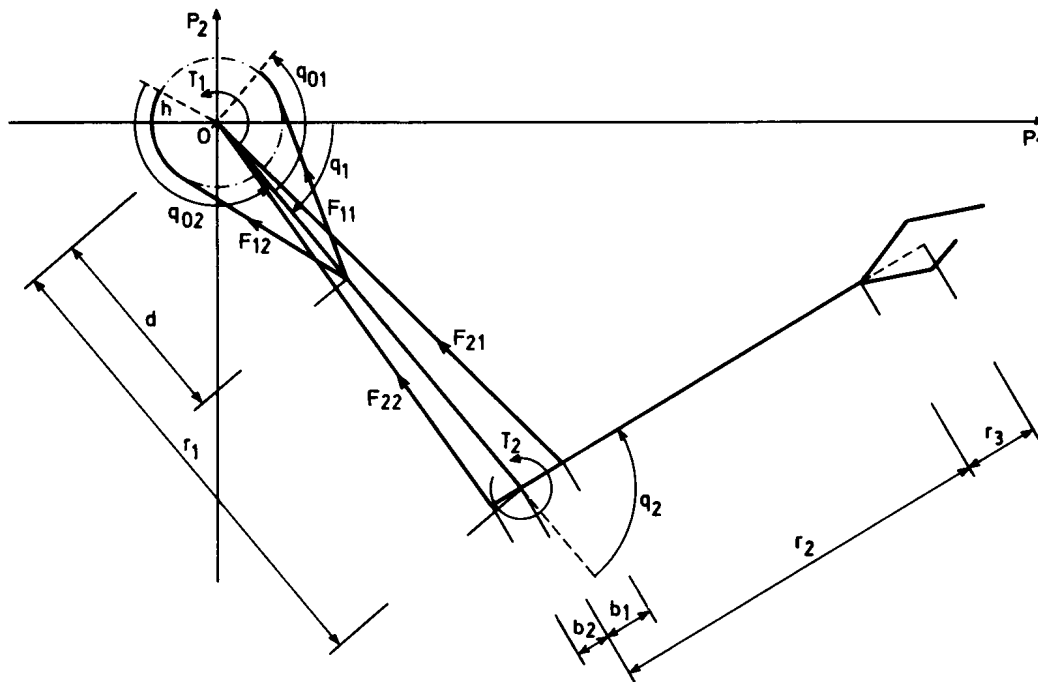


Fig. 1. Geometrical model of the human arm in the sagittal plane for the shoulder and the elbow structures.

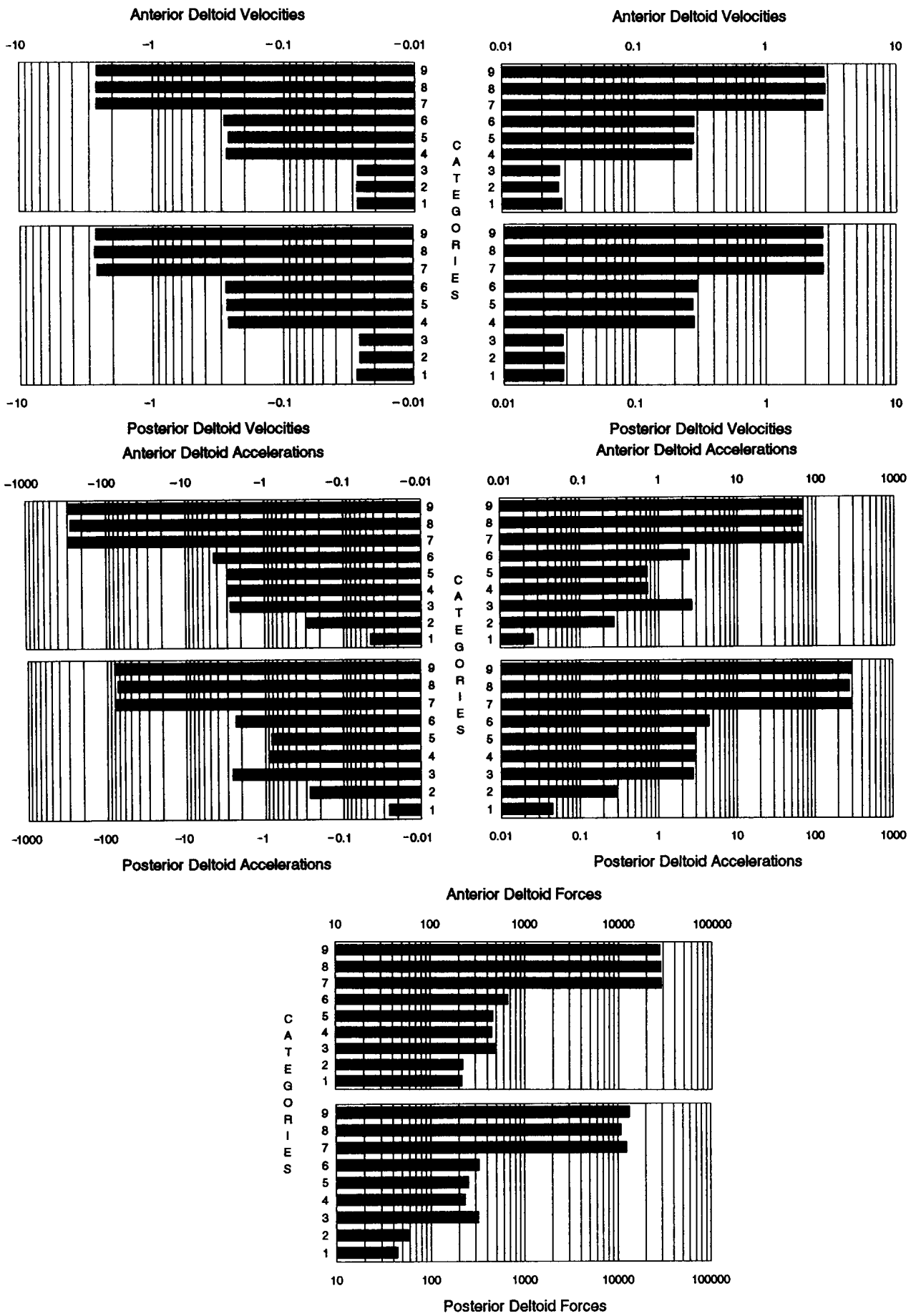


Fig. 2. Performance index for the anterior and posterior deltoids when "excited" with p.d.f.'s (6)-(8), for the nine categories of σ_V and σ_A .

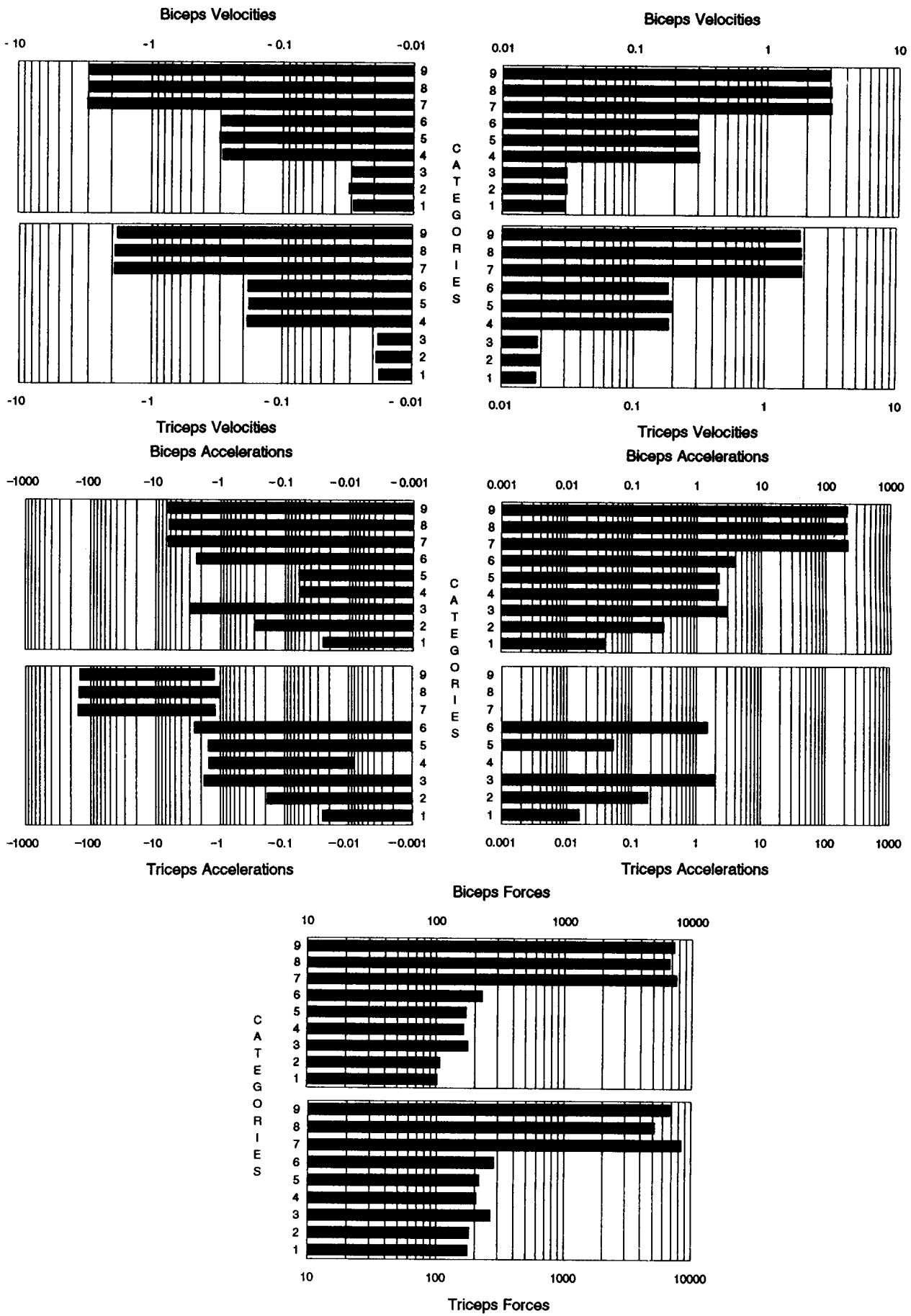


Fig. 3. Performance index for the biceps brachii and triceps brachii when "excited" with p.d.f.'s (6)-(8), for the nine categories of σ_V and σ_A .