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Robotic Analyses of Output Force Distribution Developed by Human Limbs

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Abstract

In this paper, we propose an introduction of a muscle coordinate system consisted of the bi-articular muscles as well as the mono-articular muscles instead of a conventional joint coordinate system consisted of only the mono-articular muscles without the bi-articular muscles to discuss about an interface between man and machine systems. The output force distribution developed at the wrist joint of human arm under isometric and maximal effort conditions demonstrated a hexagonal shape. Since complex muscle arrangements of human arm could be simplified into one antagonistic pair of the bi-articular muscles and two antagonistic pairs of the mono-articular muscles (functionally effective muscular strengths: FEMSs), a robot arm provided with three pairs, six muscles was built up. The robot arm operated with the muscle coordinate system demonstrated hexagonal shape output force distributions. Whereas, the robot arm operated with the joint coordinate system showed quadrangular output force distributions. A characteristics of the hexagonal force distribution made it possible to evaluate individual functionally effective muscular strengths (FEMSs) from the human arm output force distribution. The results obtained here will lead a new virtual human model into much more real than the conventional model operated with the joint coordinate system. The idea will also be useful for a human-friendly robot.

1 Introduction

To support much more progress in human-friendly robot, well discussions have been attempted on the interface between man and machine systems. To improve more the human interface, we need more knowledge about the human characteristics, and the international standardization of computer mannequin program is advanced[1,2,3]. In the computer mannequin, following measurements and evaluations are considered.

1) Static measurements and evaluations of dimensions of interference between human body and equipments (e.g. robot) or workspace.
2) Dynamic measurements and evaluations of workability or operability which seem to be originated from the muscle strengths or the joint torques.

The relationship between a force in a task coordinate system where it represents workability or operability by human arm or robot arm, and joint angles or joint torques in a joint coordinate system is widely known in robotics. In addition to this, functional characteristics of the human muscles, as joint drivers, are also discussed, such as the dynamic muscle model. Generally, the relationship between the muscle strength and the joint torque was simple in the joint coordinate system, however in the muscle coordinate system, existence of the bi-articular muscle has made it complicate. Recently, it has been elucidated that the existence of the bi-articular muscle greatly contributed to motion control and force control of the human arm[4,5,6].

In this study, the relationships between output force distribution in the task coordinate system and the muscle strengths in the muscle coordinate system of the human arm are examined utilizing two-joint robot arm provided with six actuators in terms of robotics. And, the measuring technique of the output force distribution of the human arm and the evaluation procedure of the functionally effective muscular strengths are proposed.

2 Muscle strength and output force distribution

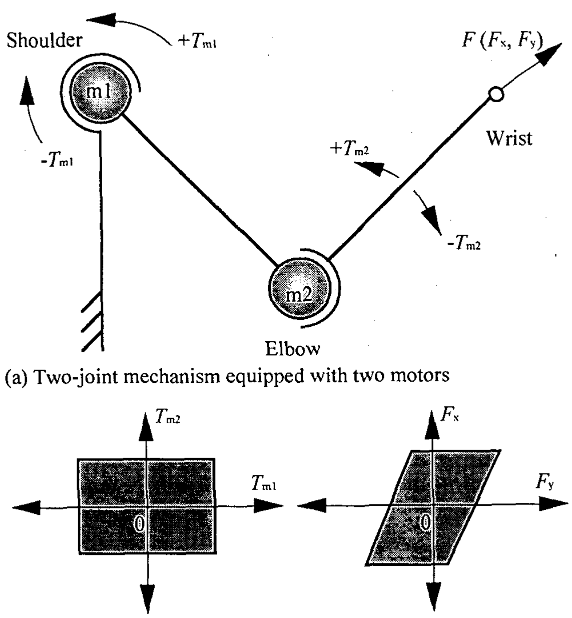
2.1 Joint coordinate system and muscle coordinate system

A typical two-joint link mechanism with two degrees

degrees of freedom is shown in Fig. 1(a). Each joint is driven by only one actuator, m1 or m2. The joint torques, T_{m1} and T_{m2}, can be expressed by the two dimensional joint coordinate system as shown in Fig. 1(b). The output force distribution $F(F_x, F_y)$ developed by the joint torques of T_{m1} and T_{m2} in the two dimensional task coordinate system is shown in Fig. 1(c). In addition, even if the actuator increases, number of degrees of freedom of its motion and number of actuators are same. It agrees with number of coordinate axes of the joint coordinate system.

In the meantime, as shown in Fig. 2(a), complicate muscular arrangements of the human arm can be simplified into three pairs of antagonistic muscles, where two antagonistic pairs of the mono-articular muscles of f1, and e1 on the shoulder joint, and of f2 and e2 on the elbow joint, and one antagonistic pair of bi-articular muscles of f3 and e3 acting on the both joints at the same time. That is to say, six muscles (actuators) are concerned for motion of the two-joint link mechanism with two degrees of freedom. The joint torques in proportion to muscle strengths are T_{f1}, T_{e1}, T_{f2}, T_{e2}, T_{f3} and T_{e3}, and they can be expressed by the three dimensional muscle coordinate system in Fig. 2(b). And, Fig. 2(c) shows the output force distribution developed in the two dimensional task coordinate system.

Like this, mechanism of the typical robot arm and mechanism of the human arm are greatly different.



(a) Two-joint mechanism equipped with two motors

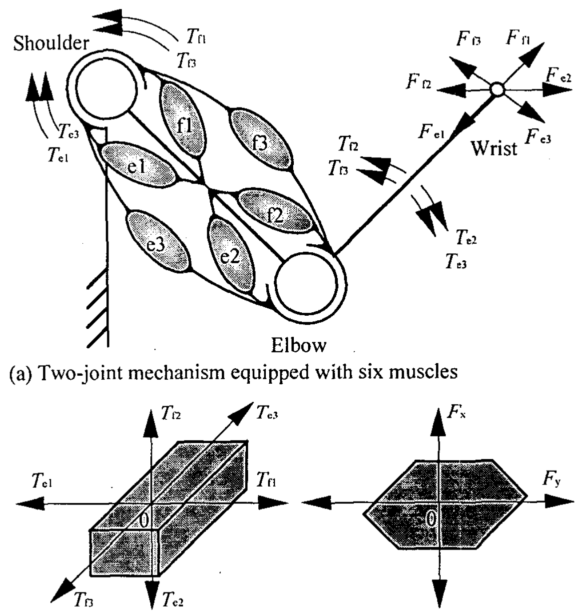
(b) Joint coordinate system (c) Task coordinate system

Fig. 1 Two-joint mechanism with two motors

2.2 Muscle strength

The muscle strengths are defined here. In Fig. 3, T_{f1}, T_{e1}, T_{f2}, T_{e2}, T_{f3} and T_{e3} are the joint torques as each muscle generated maximum strength. These are defined as a functionally effective muscular strength (FEMS). These FEMSs are determined by the maximum muscle strengths and the lengths of moment arm of the muscles. Output forces at the wrist joint generated by the FEMSs are came to be F_{f1}, F_{e1}, F_{f2}, F_{e2}, F_{f3} and F_{e3}. These output forces are determined by the FEMS, the link lengths and the joint angles. These output forces cold develop the output force distribution in the task coordinate system.

So far, in the conventional robotics even in the human kinetics, the relationship between output force distribution and muscle strengths has never been discussed clearly.



(a) Two-joint mechanism equipped with six muscles

(b) Muscle coordinate system (c) Task coordinate system

Fig. 2 Two-joint mechanism equipped with six muscles

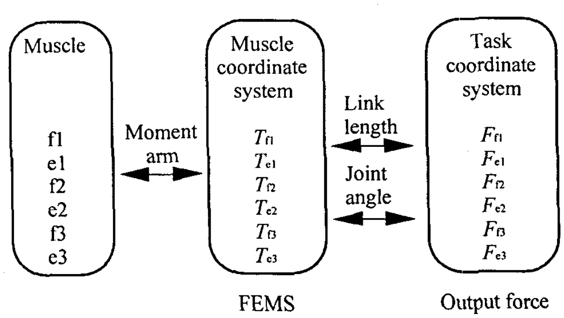


Fig. 3 Muscle strength

2.3 Output force distribution

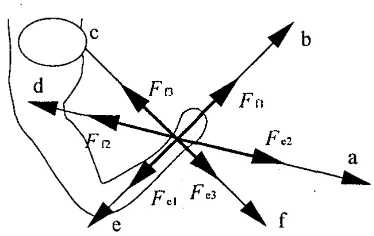
Each FEMS could develop an individual output force by its above on each direction in the task coordinate system as shown in Fig. 4. Where, F_{f1} developed by f1 exerted on distribution b; F_{e1} on distribution e; F_{f2} on distribution d; F_{e2} on distribution a; F_{f3} on distribution c; F_{e3} on distribution f. Direction a-d is passing through the shoulder joint and the wrist joint, direction b-e is along the forearm and direction c-f is parallel to the upper arm.

Output forces developed by the multiple muscle system in any direction could be derived by geometrical summation of the individual output force vectors as shown in Fig.4(b). The output force distribution obtained by such a procedure comes to be a hexagonal shape. In this shape, A ~ F show the corners of the hexagon. Characteristics of this hexagonal shape are as follows.

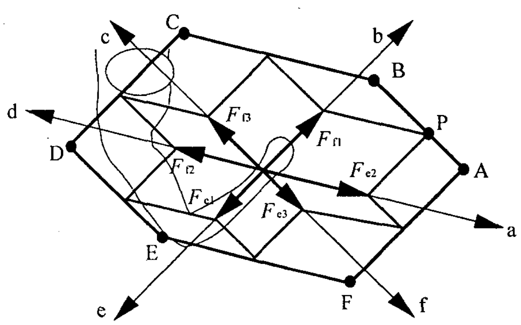
1) Opposite side lines, C-D and F-A, are parallel to the direction b-e. And, lengths of C-D and F-A are same and equal to sum of the output forces, F_{f1} and F_{e1}, developed by the FEMSs, T_{f1} and T_{e1}.

2) Opposite side lines, B-C and E-F, are parallel to the direction a-d. And, lengths of B-C and E-F are same and equal to sum of the output forces, F_{f2} and F_{e2}, developed by the FEMSs, T_{f2} and T_{e2}.

3) Opposite side lines, A-B and D-E, are parallel to the direction c-f. And, lengths of A-B and D-E are same and equal to sum of the output forces, F_{f3} and F_{e3}, developed by the FEMSs, T_{f3} and T_{e3}.



(a) Individual output forces developed by individual FEMS

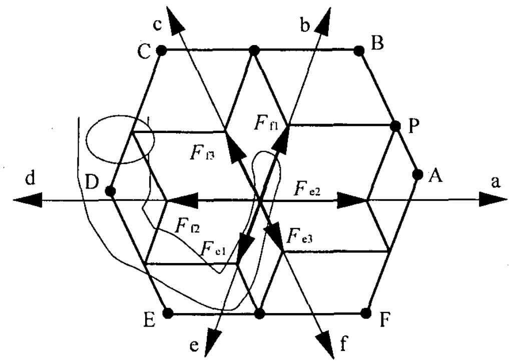


(b) Output force distribution

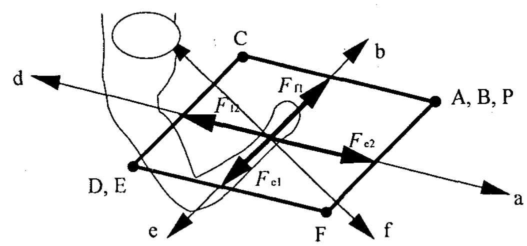
Fig. 4 Hexagonal output force distribution

In Fig. 4(b), point P on the line A-B is the direction in which the muscles of f3 (F_{f3}) and e3 (F_{e3}) change the activities. Therefore, it is possible to derive the each muscle strength independently, if the direction of point P is proven.

In fig. 5(a), it is shown that the hexagonal output force distribution varied with changes in the joint angles, even if the FEMSs are the same as the Fig. 4. In Fig. 5(b), the output force distribution developed by the joint coordinate system without the bi-articular muscles comes to be a quadrangle shape.



(a) Output force distribution changed with cahnges in joint angles



(b) Output force distribution operaded with the joint coordinate system, without bi-articular muscles

Fig. 5 Properties of Hexagonal output force distribution

3 Experiments

3.1 Robot arm

A two-joint robot arm provided with six pneumatic artificial rubber actuators (maximum contractile force: 210N) was constructed in a horizontal plane. The actuators were installed on the two-joint link mechanism (length: 300mm each) via sprockets and chains. A load cell was installed at the end point.

Activation levels of the sctuators to exert the maximum output forces at teh end point in all round directions, 360°, where calculated theoretically, as shown in Fig. 6.

The robot arm, in with the three pairs, six actuators were activated according to the pattern shown in Fig. 6, could demonstrate hexagonal output force distributions as shown in Fig. 7, filled circles. The white line hexagons were diuretically calculated.

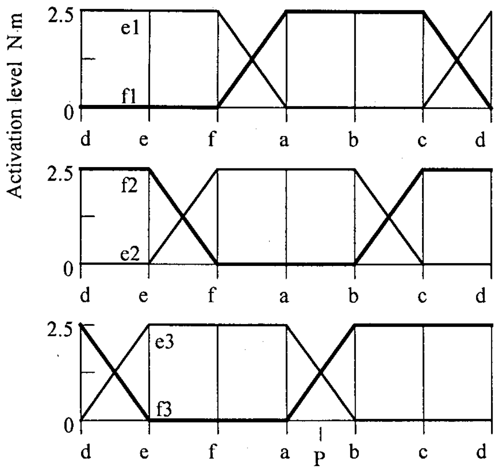


Fig. 6 Activation level pattern of three pairs, six actuators to exart the maximum output force at the end point

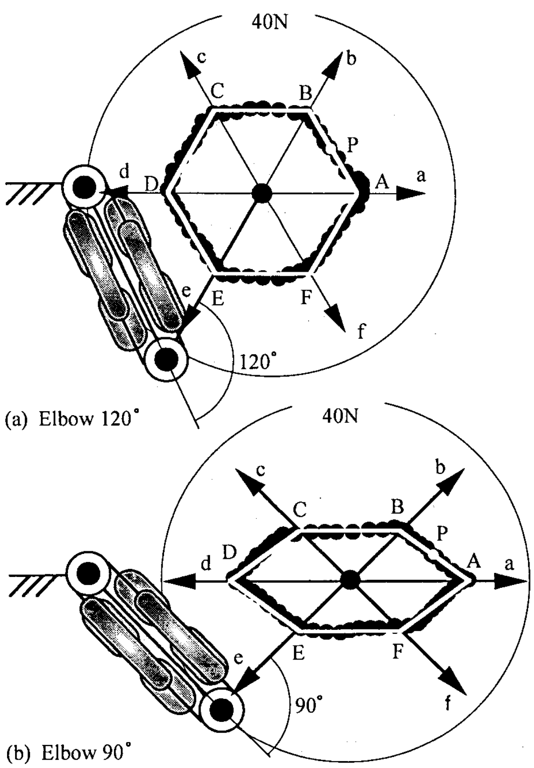


Fig. 7 Output force distribution developed by the robot arm

3.2 Human output force distribution and FEMS

For the human arm, the output force distribution at the wrist joint was measured. A measuring equipment is shown in Fig. 8. This equipment is constituted of frame, sheet, belts, grip and load cell which can detect the two-dimensional force. Farther, there are amplifier, personal computer and monitor.

Subject's trunk was fixed by belts in order to hold their posture, and his wrist joint was fixed by cast or bandage on the grip coupled to the load cell. Subjects were requester to exert the maximum output force to any direction directed through the CRT monitor for 1 ~ 2 seconds. The force recordings were repeater to cover 360° with appropriate angular ranges.

The force recordings were plotted as shown in Fig. 9, and were approximated into hexagons. The hexagonal shapes were strained from the one of the robot arm, and it might be caused by differences in FEMSs, the link lengths and the moment arm lengths.

The electrical activities of the six muscles (FEMSs) were recorded utilizing the conventional surface electrodes during the force recordings, simultaneously. The integral EMGs (IEMGs) were normalized into percentage (%) as shown in Fig. 10.

It should be noted that the IEMGs pattern of Fig. 10 is quite similar to the activity level pattern of actuators as shown in Fig. 6. The results obtained above strongly suggested that the FEMSs could be estimated from the output force distribution in the human arm.

From the output force distribution shown in Fig. 9, it is possible to obtain the sum of the antagonistic muscle strengths in proportion to the lengths of the side lines of the output force distribution. Further, it is possible to separate into the individual muscle strength, if the point P is proven in which the muscle activities reversed. And, from the elbow angle and the link lengths, it is possible

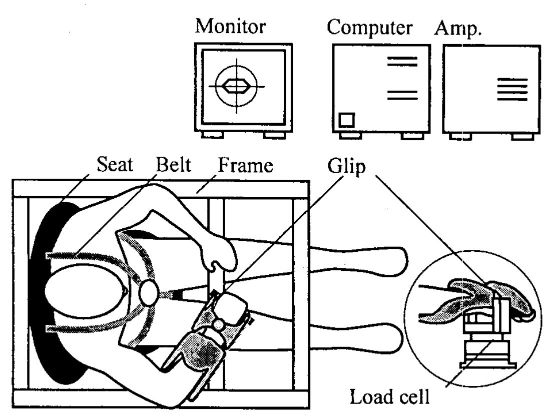


Fig. 8 Output force distribution testing

to estimate the FEMSs. The results are shown in Table 1. Where, (a) and (b) are correspondent to Fig. 9. Point P was obtained from the IEMG (Fig.10). Though the muscle strengths are different because of changes in the elbow angles, but the FEMSs should be same theoretically (Table 1).

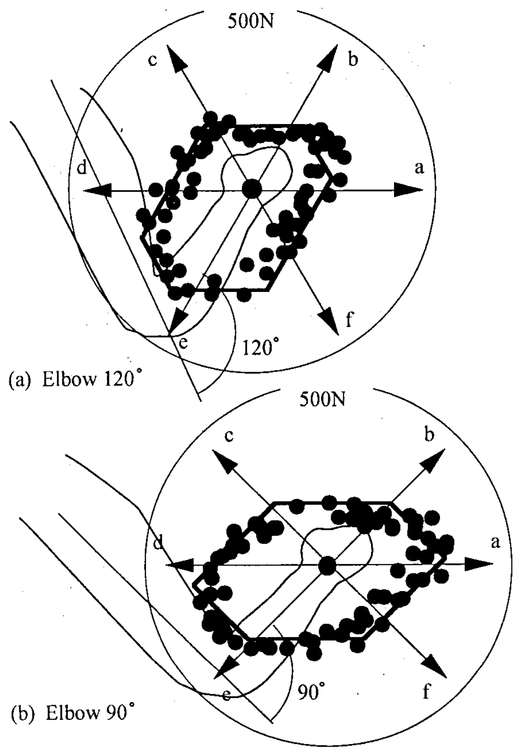


Fig. 9 Output force distribution in the human

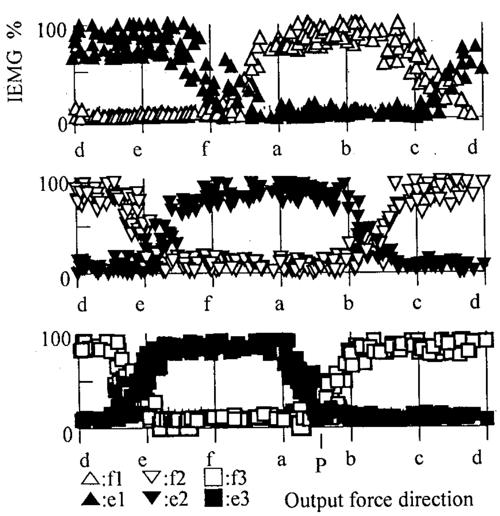


Fig. 10 IFMGs of three pairs, six muscles in the human arm

Fig. 11 and table 2 show the results of the output force distributions and the FEMS of four subjects. In table 2, the point P was obtained according to an evaluation function in which the difference in the antagonistic muscle strengths to be minimized.

Here, the hexagonal shapes (Fig. 11) and the FEMSs (Table 2) indicated that the human output force characteristics mighit be different from subject to subject.

During the evaluation procedure of the FEMS, it was confirmed that combinations of the FEMS to develop any constant hexagonal shape infinitely existed. This means that even if one muscle deteriorated, the other muscles could compensate the loss of its muscular strength to maintain the original hexagonal shape. One may say this might be flexible adaptability of a human

Table 1 Derivation of FEMS

			(a)	(b)
Sum of muscle strengths	(N)	$F_{f1}+F_{e1}$	352.1	331.2
		$F_{f2}+F_{e2}$	264.2	320.8
		$F_{f3}+F_{e3}$	169.5	144.0
Muscle strength	(N)	F_{f1}	148.3	136.4
		F_{e1}	203.8	194.8
		F_{f2}	169.8	188.7
		F_{e2}	944.4	132.1
		F_{f3}	56.5	48.0
		F_{e3}	113.0	96.0
FEMS	(N·m)	T_{f1}	32.1	34.1
		T_{e1}	44.1	48.7
		T_{f2}	36.8	33.4
		T_{e2}	20.4	23.4
		T_{f3}	12.2	12.0
		T_{e3}	24.5	24.0

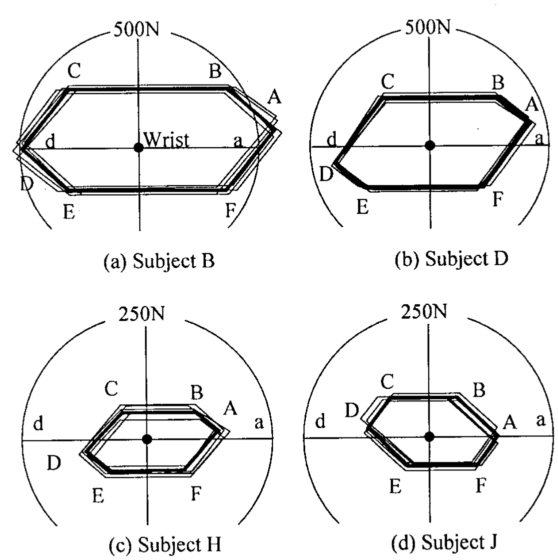


Fig. 11 Output force distribution of four subjects

body. As shown in Fig. 12, the output force distribution developed by the muscle coordinate system demonstrated a hexagonal shape, whereas the one developed by the joint coordinate system, a quadrangular shape. The biggest output force directions are different between the two systems. Conventional muscle strength tests generally performed in rehabilitation and sport sciences used to be discussed in terms of the joint coordinate system, but never, in terms of the muscle coordinate system.

Table 2 FEMS of four subjects

Subject \ FEMS N·m	T_{f1}	T_{e1}	T_{f2}	T_{e2}	T_{f3}	T_{e3}
B	49.6	16.8	54.3	54.4	67.8	26.5
D	54.4	26.4	41.3	41.2	16.7	13.7
H	26.8	22.7	18.8	18.8	14.4	11.0
J	13.8	11.8	20.9	20.9	24.2	14.7

4 Conclusions

Results obtained in the present experiments, strongly indicated that an interface between man and machine systems should be discussed in terms of the muscle coordinate system instead of the conventional joint coordinate system.

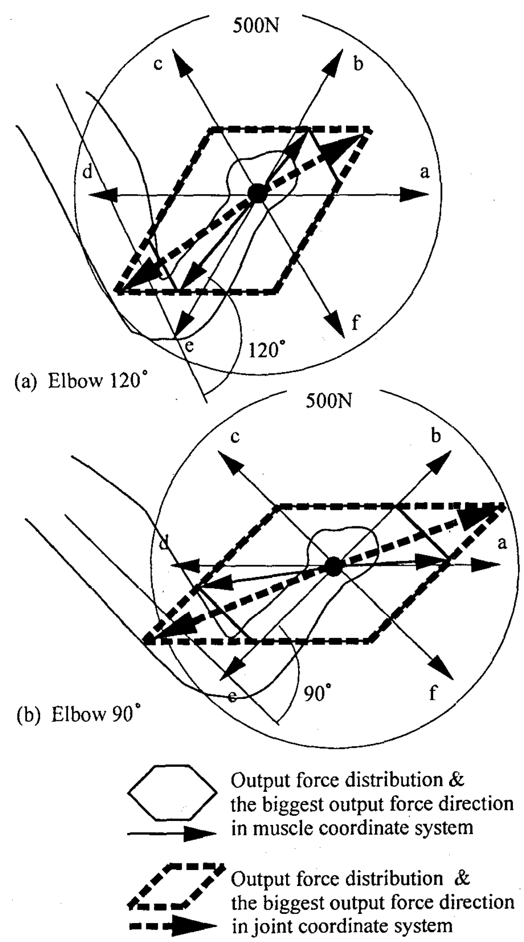


Fig. 12 Output force distribution in muscle and joint coordinate systems

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