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CONTROL OF FINGER STIFFNESS IN HAND PROSTHESES

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1 INTRODUCTION

The objective of this research is to improve the performance of hand prostheses by controlling finger stiffness. In commercially available prostheses, finger stiffness cannot be modulated. Yet, stiffness may be helpful to stabilize a grasp and enhance the performance of a prosthesis. For instance, stiffness partially determines finger response to a perturbation. For a given displacement, the orientation of the restoring force varies with stiffness. Moreover, stiffness is the inverse of compliance: for a given external force, a low finger stiffness would result in a large finger displacement while a high stiffness results in a small displacement.

In order to establish guidelines for the design of a prosthesis with compliant fingers, a theoretical study of human finger stiffness has been initiated. We want to investigate the range of endpoint stiffness in human finger.

2 FINGER ENDPOINT STIFFNESS

For a given displacement $\mathbf{X} = (\Delta x, \Delta y)$ at the endpoint, we want to know the restoring force, $F = (f_x, f_y)$, caused by that displacement. The endpoint stiffness **K** is a two-by-two matrix relating the endpoint restoring force, **F**, to the displacement **X**:

$$\mathbf{F} = -\mathbf{K}\mathbf{X} \qquad (1)$$

This paper analyses the variation in the orientation of the principal eigenvector of the endpoint stiffness matrix of two simple mechanical models: a finger with two phalanges and one with three phalanges. Both models have symmetric endpoint stiffness matrix. Thus, their behavior is elastic [2]. Hogan (1985) demonstrated that, in this case, the restoring force is given by the gradient of the potential function. The potential function can be represented by an ellipse where the orientation of its major axis is given by the orientation of the principal eigenvector of the stiffness matrix.

In this paper, we use the orientation of the principal eigenvector as an indication on the range of endpoint stiffness.

2.1 Two Phalanx Model

A finger having two phalanges can be modeled as a two degree of freedom manipulator as represented in Figure 1.

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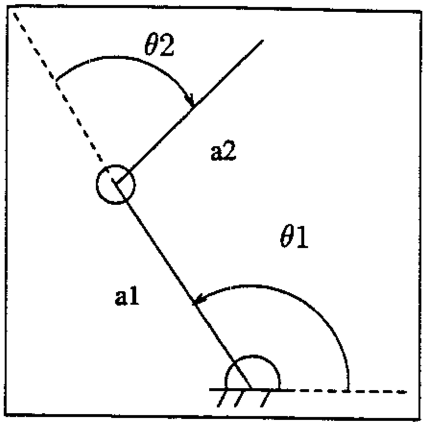

Figure 1:Two degree of freedom manipulator.

Hogan (1980) studied the effect of single-joint and two-joint muscles for a two degree of freedom manipulator that represented the human arm. He observed that, with two-joint muscles, the principal eigenvector of the stiffness tensor of the end point effector can be oriented in almost all directions.

For example, in Figure 2, the orientation of the manipulator's principal eigenvector is drawn in a specific configuration for single-joint and two-joint muscle cases.

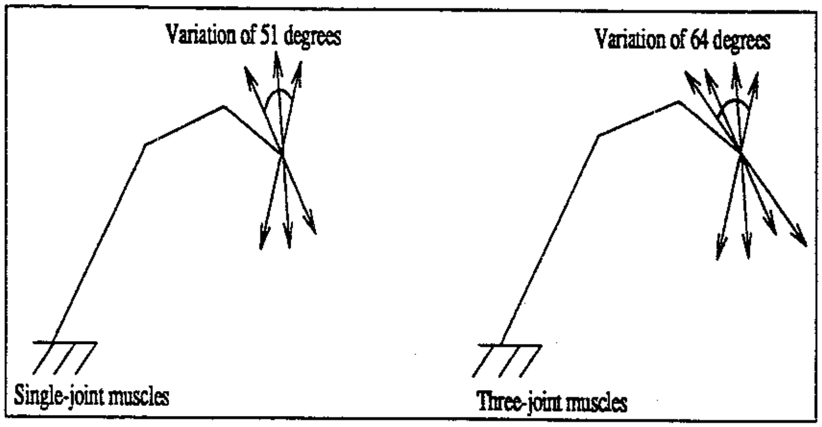

Figure 2: Orientation of principal eigenvector with a1 =40 cm, a2=40cm, θ1=130 degrees,θ2=-90degrees.

For the configuration shown in Figure 2, the orientation of the principal eigenvector can vary from 45 to 175 degrees in the case of two-joint muscles and from 130 to 175 degrees in the case of single-joint muscle. This increase means a greater range in the orientation of the restoring force.

2.2 Three Phalanx Model

A finger with three phalanges is modeled as a three degree of freedom manipulator as shown in Figure 3.

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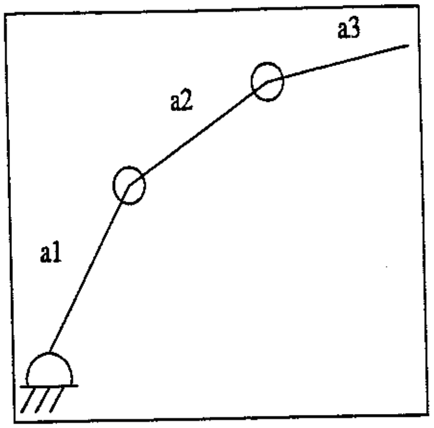

Figure 3: Three degree of freedom manipulator.

The endpoint stiffness of this manipulator is obtained from the geometry as: equation

$$\mathbf{C} = \mathbf{J}\mathbf{K}\theta^{-1}\mathbf{J}^{T} \tag{2}$$

$$\mathbf{K} = \mathbf{C}^{-1} \tag{3}$$

where, **C** is the compliance matrix,
K is the endpoint stiffness matrix,
J is the manipulator's jacobian,
Kθ is the joint stiffness matrix.

For a given configuration, the endpoint stiffness matrix depends on the joint stiffness matrix. Assuming single-joint muscles to each joint leads to a diagonal joint stiffness matrix. By changing the diagonal terms of this matrix, the orientation of the principal eigenvector varies as shown in Figure 4.

The addition of three-joint muscles to this model give a joint stiffness matrix of the form:

$$\mathbf{K}_\theta = \begin{bmatrix} a+d & d & d \\ d & b+d & d \\ d & d & c+d \end{bmatrix} \tag{4}$$

where, a, b, c are the joint stiffness produced by single-joint muscles at joint 1, 2 and 3 respectively and d is the joint stiffness produced by three-joint muscles. This produces an increase in the range of principal eigenvector's orientation as obtained for the two degree of freedom manipulator. However, for the configuration in Figure 4, the range of orientation is increased by only 13 degrees.

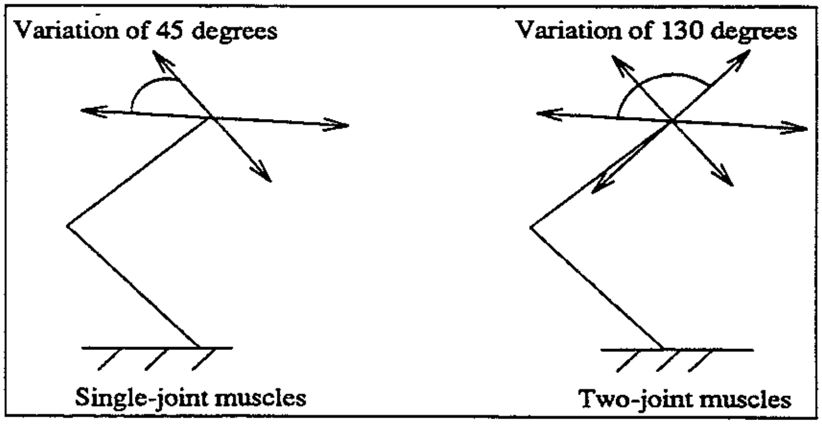

Figure 4:Orientation of principal eigenvector with $a1=5cm$, $a2=2.5cm$, $a3=2cm$, $\theta1=55degrees$, $\theta2=-29degrees$, $\theta3=-46degrees$.

3 DISCUSSION

In the two finger models, the arrangement of muscles around the joints influences the variation of the endpoint stiffness matrix. As expected, the addition of multi-joint muscles increases the range of orientation of the principal eigenvector in both models. For the configuration used, the increase in the range of the principal eigenvector's orientation caused by the addition of multi-joint muscles is smaller for the 3 phalanx model than the increase for the 2 phalanx model. Different finger configurations would lead to different results.

The ability to vary the endpoint stiffness is an important aspect of a mechanical system. The desired response of a grasped object following a perturbation can be control by choosing the appropriate endpoint stiffness. In order to get a better control of the grasped object following a perturbation and thus, improve the performance of hand prostheses, the endpoint stiffness should be one of the design specifications. Our choice for the appropriate range of endpoint stiffness in the design of hand prostheses will be based on human finger behavior. The models presented in this paper give an indication on the possible endpoint stiffness of simple mechanical system having two and three phalanges. It offers a starting point to analyse mechanical systems that will best fit the design requirements for hand prostheses.

4 FUTURE WORK

The joint stiffness matrix of a real finger is not the same as those presented in this paper. In the human finger, some tendons pass through one, two or three joints and insert at several places to the bones. The next step of this research will be to develop a mathematical model based on the anatomy and geometry of the fingers. This model will represent the endpoint stiffness matrix for different configurations. The interest of this model is to predict finger stiffness and the extent to which it can be modulated. We intend to perform an experiment to measure the end point stiffness of the thumb, the index and middle finger while executing a three finger tip grip. The effect of the object size as well as the magnitude of the contact force with the object will be investigated. This experiment will be conducted in order to validate the mathematical model and to study human finger behavior. Finally, the prosthesis design requirements necessary to achieve the observed finger stiffness or the desired object behavior will be determined.

REFERENCES

[1] Hogan, N., ''Mechanical impedance control in assistive devices and manipulators", Proc. 1980 Joint Autom. Controls Conf. paper TA 10-b, 1980.

[2] Hogan, N., 'The mechanics of multi-joint posture and movement control", Biol. Cybern., 52, 315-331, 1985.