A Constant Tendon Moment Arms Finger Model in the Sagittal Plane

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ABSTRACT

Finger movements in the sagittal plane mainly consist of flexion and extension about the metacarpophalangeal(MCP) and proximal interphalangeal(PIP) joints. A kinematic finger model was developed with the assumption of constant tendon moment arms. Equations of static equilibrium were derived for the finger model using the principle of virtual work. Equations of static equilibrium for the finger model were indeterminate since only three equations were available for five unknown variables(forces). The number of variables was reduced based on information on muscular activities in finger movements. Then the amounts of forces which muscles exerted to maintain static equilibrium against external loads were computed from the equilibrium equations. The muscular forces were expressed mathematically as functions of finger positions, tendon moment arms, lengths of phalanges, and the magnitude and direction of external load.

The external finger strength were computed using the equations of muscular forces and anatomical data. Experiments were performed to measure finger strengths. Measurements were taken in combinations of four finger positions and four directions of force exertions.

Validation of the finger models and of procedure to estimate finger strengths was done by comparing the results of computations and experiments. Significant differences were found between the predicted and measured finger strengths. However, the trends of finger strengths with respect to finger positions were similar in both the predicted and measured. These findings indicate that the finger model and the procedure to predict finger strengths were correctly developed.

I. INTRODUCTION

Major finger movements, extension and flexion, occur in the sagittal plane. These finger movements can be described by individual or coordinated movements of three phalanges of the finger: proximal, middle, and distal. The proximal and middle phalanges can move independently, but the movement of the distal phalanx is largely dependent on the movement of the middle phalanx. Therefore, the finger is frequently simplified to a two-joints (bi-articular) system.

Functions of the finger can be understood by developing biomechanical model and by analyzing the force associated with force exertions. The purpose of this study is to develop a biomechanical model of the finger and to validate it. Since the basic movements of the finger are flexion and extension, the biomechanical finger model is in the sagittal plane. It includes only static exertions about the metacarpophalangeal(MCP) and proximal interphalangeal(PIP) joints. Validation of the model is performed by comparing the predicted finger strengths to experimental results.

II. FUNCTIONAL ANATOMY OF THE FINGER

The finger is a multiarticular system. Muscles of the finger are divided into two groups by their locations: intrinsic and extrinsic muscles. Intrinsic muscles are the interossei and lumbricals. Extrinsic muscles are divided again into two groups by their functions: flexors and extensors. The flexors consist of the flexor digitorum profundus(FDP) and the flexor digitorum superficialis(FDS). The extensor digitorum communis(EDC) is the major extensor.

Muscles of the finger act across two or three joints, usually by having their tendons cross a joint or joints without attachment to bony elements. Tendons of the interossei and lumbricals merge into the tendon of the EDC and are connected with each other. The lumbricals arise from the tendons of the FDP. Therefore, the force generated by one muscle may act on several joints; conversely, forces from severa. ·nuscles may act on one joint.

Roles of the muscles :n finger joint movements are summarized in Table 1.

Table 1. Roles of the muscles in finger joint movement.

Joint Movem't / Muscle	MCP		PIP		DIP		Other Movements
	Flex.	Ext.	Flex.	Ext.	Flex.	Ext.	
EDC		X		X		X	
FDS	X	(X)	X				
FDP			X		X		
Interossei	X			X		X	abduct & adduct fingers
Lumbricals	(X)			X		X	rotate fingers
Flexor Carpi Radialis							flex the wrist
Extensor Digiti Minimi		X		X		X	extend the little finger
Extensor Indicis		X		X		X	extend the index finger

legend (X) : inconsistent activation

EDC : Extensor Digitorum Communis
FDS : Flexor Digitorum Superficialis
FDP : Flexor Digitorum Profundus

Ⅱ. BIOMECHANICAL FINGER MODEL

A finger model was developed based upon the functional anatomy and physiology of the hand and finger movements. The finger model reflects the anatomical structure of the finger and includes all activities of the muscles in flexion and extension of the finger joints. This finger model has the following features:

1) The finger movements are performed in the sagittal plane.
2) The finger joints are pin joints.
3) Five muscles are involved in the finger flexion and extension.
4) The combined extensor muscle inserts into the bases of the proximal, middle, and distal phalanges.
5) The flexor digitorum profundus inserts into the base of the distal phalanx.
6) The flexor digitorum superficialis inserts into the body of the middle phalanx.
7) The combined interosseous muscle inserts into the bases of the proximal and middle phalanges and the lateral band. (In reality, there is no physical insertion of the interosseous muscle into the proximal phalanx. In this study, however, an imaginary insertion of the interosseous muscle into the base of the proximal phalanx is installed to reflect the contribution of the interosseous muscle to flexing the MCP joint).
8) The lumbrical muscle inserts into the base of the middle phalanx and the lateral band.
9) The tendon moment arms at every finger joint are constant during finger flexion and extension.

The finger model developed in this study is schematically expressed in Figure 1.

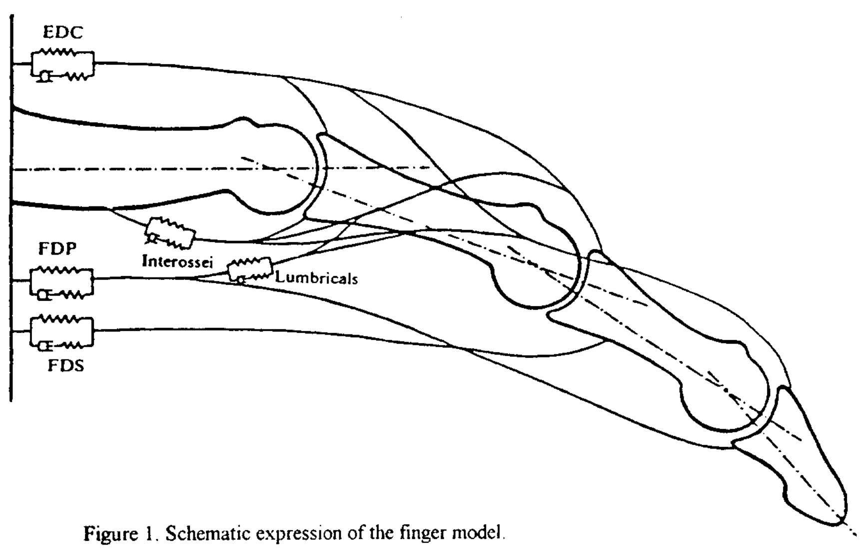

Figure 1. Schematic expression of the finger model.

EDC: Extensor Digitorum Communis, FDP: Flexor Digitorum Profundus, FDS: Flexor Digitorum Superficialis.

The tendon excursions based on this finger model are described mathematically as follows:

Extensor Digitorum Communis

$$X_E = r_{E1}\theta_1 + r_{E2}\theta_2 + r_{E3}\theta_3$$

Flexor Digitorum Profundus

$$X_P = -r_{P1}\theta_1 - r_{P2}\theta_2 - r_{P3}\theta_3$$

Flexor Digitorum Superficialis

$$X_S = -r_{S1}\theta_1 - r_{S2}\theta_2$$

Interossei

$$X_I = -r_{I1}\theta_1 + r_{I2}\theta_2 + r_{I3}\theta_3$$

Lumbricals

$$X_L = -r_{L1}\theta_1 + r_{L2}\theta_2 + r_{L3}\theta_3$$

,where X represents the tendon excursion, r represents moment arm of the tendon, and θ represent the angle of finger joint. Subscripts E, P, S, I, and L of X represent the corresponding muscles, and subscripts 1,2, and 3 represent the MCP, PIP, and DIP joints, respectively.

If there is an external load acting on the fingertip, the external load can be divided into three torques which act at the MCP joint (T1), PIP joint (T2), and DIP joint (T3). If the finger is assumed to be in static equilibrium, the amount of work done by all muscles and the external load becomes zero. Thus,

$$F_E\delta X_E + F_P\delta X_P + F_S\delta X_S + F_I\delta X_I + F_L\delta X_L$$
$$+(T1+T2+T3)\delta\theta_1 + (T2+T3)\delta\theta_2 + T3\delta\theta_3 = 0$$

,where F stands for the muscular force, δX stands for the increment of the tendon excursion, X , and $\delta\theta$ stands for the increment of joint angle. Substituting $X_E, X_P, X_S, X_I,$ and X_L in tendon excursion equations into this equation, and solving for $\delta\theta_1, \delta\theta_2,$ and $\delta\theta_3$, the following simultaneous equations are obtained:

$$F_E r_{E1} - F_p r_{P1} - F_S r_{S1} - F_I r_{I1} - F_L r_{L1} + T1 + T2 + T3 = 0$$
$$F_E r_{E2} - F_p r_{P2} - F_S r_{S2} + F_I r_{I2} + F_L r_{L2} + T2 + T3 = 0$$
$$F_E r_{E3} - F_p r_{P3} + F_I r_{I3} + F_L r_{L3} + T3 = 0$$

These force equilibrium equations are indeterminate. Even with known values for the tendon moment arm, r, and for the external torque, T, there are still five unknown muscular forces in this set of three equations. There are several ways to solve this problem. One is to use a mathematical technique which utilizes linear programming. Another is to use the results of EMG studies, which provide information of muscle activations for a specific finger movement. The latter solution is used in this study.

The equations are solved for muscular forces which are expressed as functions of mechanical leverages and physiological capabilities of the muscles. Tendon moment arms, phalangeal lengths, and muscular capabilities are treated as parameters whose values could be measured. Therefore, muscular forces are expressed as functions of finger positions and torques acting on the finger joints. the torques on the finger joints are determined by the magnitude and direction of an external load and phalangeal lengths. Since phalangeal lengths are treated as parameters, muscular forces are functions of finger positions and directions of forces.

Ⅳ. FINGER POSITION AND FINGER STRENGTH

From solutions of equilibrium equations and data collected from literature and measurement, finger strengths were computed at various finger positions and directions of force exertions. To validate the finger model and procedure to derive the solutions of equilibrium equations, finger strengths were measured for combinations of finger positions and four directions of force exertions. Predicted finger strengths at the four directions of force exertions with standard variations are compared with the measured finger strengths in Figure 2, 3, 4, and 5.

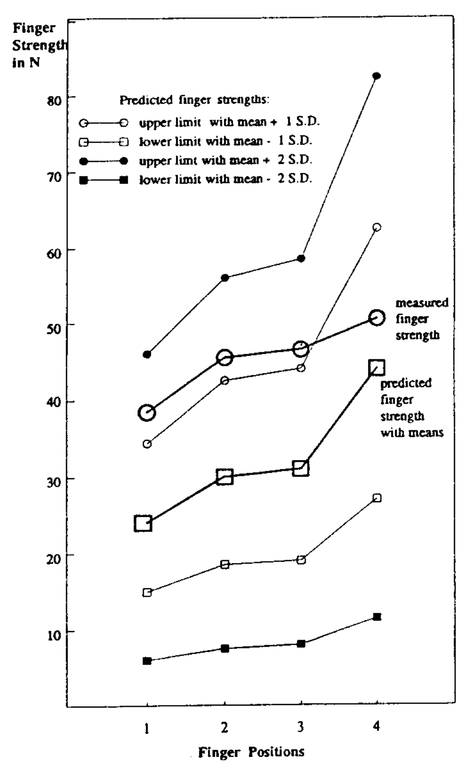

Figure 2. Predicted and measured finger strengths in downward force exertion.

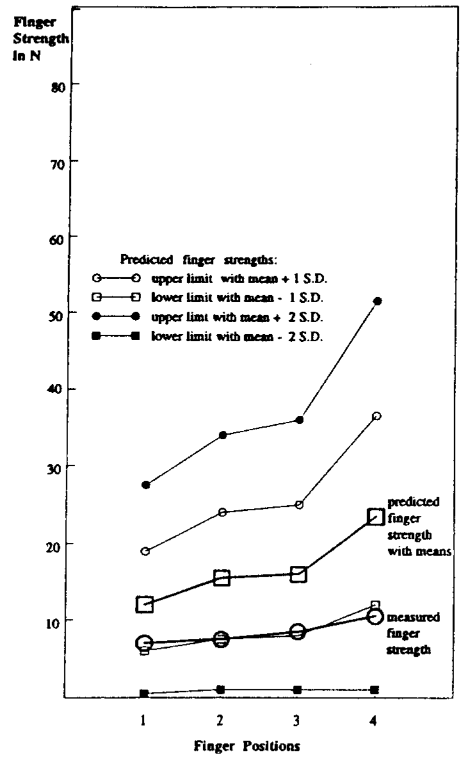

Figure 3. Predicted and measured finger strengths in upward force exertion.

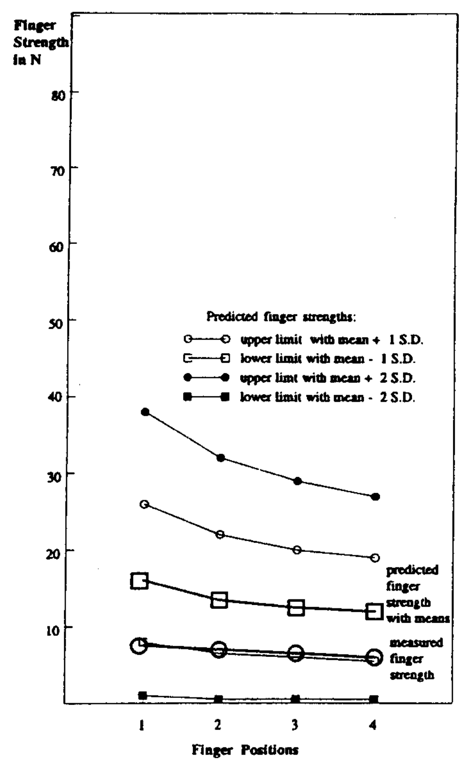

Figure 4. Predicted and measured finger strengths in forward force exertion.

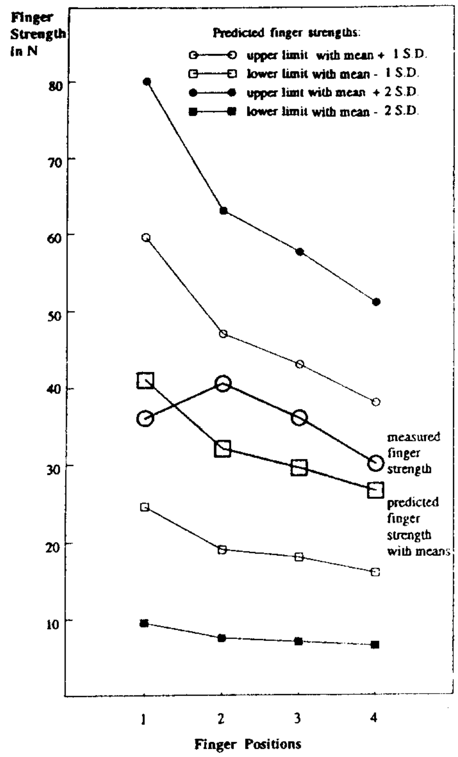

Figure 5. Predicted and measured finger strengths in backward force exertion.

V. RESULTS AND ANALYSES

Significant differences were found between the predicted and measured finger strengths. Finger strengths in finger flexion exertions were underestimated by computation while those in finger extension exertions were overestimated. These results were considered to be from the data which were adopted from Brand (1985) and Ketchum et al.(1978), and were used to predict the finger strengths. However, measured finger strengths were within the ranges plus and minus one standard deviation about the means of predicted finger strengths.

Although there are differences in the values of finger strengths, trends of finger strength variations with respect to finger positions and directions of force exertions are similar in the predicted and measured values. Magnitudes of finger strengths are determined by the anthropometric and physiological data while the trends of variations are determined by the finger model itself. This seems to indicate that the finger model and the procedure to predict finger strengths in this study were correctly developed.

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