DEVELOPMENT AND VALIDATION OF A 3-DIMENSIONAL DYNAMIC SIMULATION OF HUMAN FINGER MOVEMENT

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INTRODUCTION

In normal and pathological conditions, the movement of the hand is a very complex interaction of active and passive forces. Newer techniques, such as computer-aid modelling have been developed that are capable of providing three-dimensional perspectives, and are more advantageous for generating realistic information on hand mechanics. Biomechanical study of the finger during various hand functions in normal and pathological states provides a sound basis for the development of finger joint protheses and the rationalization of reconstructive procedures in hand surgery. The finger is considered as a linkage system of intercalated bony systems balanced by muscle and tendon forces and joint constraints. The hand, as a mechanical structure, exhibits a high degree of complexity which has tended to lead to descriptive studied of small functional components. The purpose of this paper is to develop and validate a 3-dimensional forward dynamic model of human index finger to study the behaviour of the normal finger and which can be used to examine the complex relationship between the active muscle force and the passive elasticities resident in the hand.

REVIEW OF RELATED LITERATURE

Many investigations of the biomechanics of the hand and analytical studies of tendon forces and joint torques in static hand position have been conducted. For example, An et al. (1988) using biplanar X-ray technique established a three-dimensional normative model of the hand based on the anatomical study of normal hand specimens. It can derive the tendon location, excursions and tendon moment arm under various functional configurations. But few investigations of dynamic characteristics of human hand have been found. Wells, et al (1985) presented a planar four segment model of index finger to examined the passive elastic force during unloaded finger movement. Buchner, et al. (1988) presented a kinematic and dynamic model of human finger to study the mechanism of extension expansion. They confirmed that not only the middle band is able to extend the distal phalanx, but also the lateral band bears a certain amounts of the load in both extension and flexion position of finger. Darling, et al (1990) suggested that muscle action was necessary both to produce movement and to counterbalance the interaction torque arising because of the segmental linkage. Thus a muscle's contribution to movement production may be motion-dependent and not determinable from the static analysis that currently are used to describe finger muscle function.

APPROACH

The purpose of this paper is to develop and validate a forward dynamic model of the human finger. The forward solution approach allows for model validation by loading the tendons of cadaver hands, observing the finger behaviour, and comparing this behaviour to model predictions. A planar index finger model was implemented as a deterministic mathematical model using ADAMS (Automatic Dynamic Analysis of Mechanical Systems, FDS are loaded, the final angle of model prediction are smaller than the cadaver tests. We believe that the major reason for this is that the extension expansion was simplified as a single tendon. The lack of lateral bands means that greater tendon excursions are required of the single extensor tendon to achieve a given degree of flexion. The larger passive elasticities generated in the extensor muscles tends to restrict flexion of the joints.

Table 1. Comparison of two models of the final joint angles for 10 N force applied to each muscle separately. A = No muscle passive elastic force. B = With muscle passive elastics. C = Range of three cadaver test from unpublished data, Ranney et al (1987).

		MP	PIP	DIP
NO LOAD	A	(--)	(--)	(--)
	B	23	20	0.5
	C	(18→40)	(20→48)	(-5→+5)
FDP	A	56	50	55
	B	36	30	28
	C	(52→54)	(35→72)	(7→35)
FDS	A	63	60	-18
	B	51	45	-8
	C	(70→80)	(60→109)	(0)
LUM	A	57	9	-16
	B	53	9	-3
	C	(70→80)	(0→12)	(-5→0)
EDC	A	-25	-14	-25
	B	-10	9	-10
	C	(-17→12)	(20→40)	(-8→+5)
INT	A	52	8	-16
	B	44	12	-2
	C	(--)	(--)	(--)

However, with the passive elastic properties included, the rest position of the unloaded finger is obtained from the model. Furthermore, when only the extension tendon is activated, with the involvement of the passive elastic properties resided in all muscles, the model B can predict the swan-neck or zig-zag deformity where the MP joint hyperextended and PIP joint flexes under a tension of the stretched flexor muscles passive tension, to produce the characteristic "claw" hand.

RECOMMENDATION

It is well known that the extension expansion includes one middle band and two

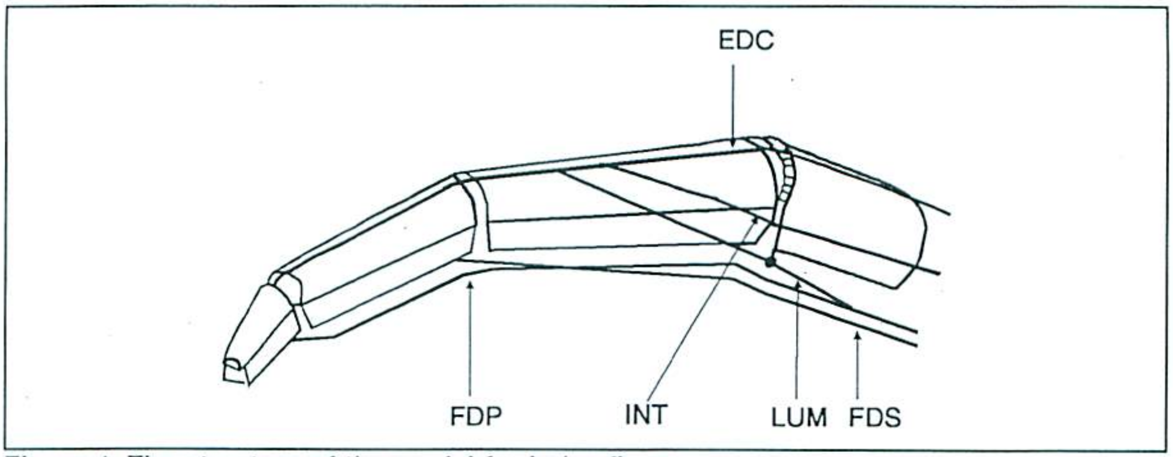

Figure 1. The structure of the model for index finger.

Mechanical Dynamics, Inc) which is a software package for simulating the force and motion function of rigid body in three dimensions. Four segments and five muscles, flexor digitorum profundus (FDP) and superficialis (FDS), extensor digitorum communis (EDC), lumbricalis (LUM), and the interossei (INT) are presented in the model. The structure of the finger model is shown in Figure 1. In this model the extensor tendon was represented simply as a single structure. Mathematical models of the hand, especially the forward simulation requires quantitative description of the mechanical and properties of the hand and forearm tissues. Musculoskeletal parameters such as tendon moment arms were obtained from the data of An et al (1983), and joint stiffness from Brand (1975) and Micks and Reswick(1981).

Initially, only the active muscle force and joint constraints were simulated in the model to obtain the final equilibrium position of each joint (Model A). Because the passive force-length properties of the musculature have been found to be important in unloaded prehensile activities, the passive elastics properties of the muscle are also included, Ranney et al (1987). The model input consisted of the force/time history of the five muscle forces and the outputs are the kinematics of the three joints. Only the sagittal motion and the final equilibrium positions are reported here. The force function is a step input: F(t)=10 N. The force was applied to each muscle separately.

In order to establish the validity of the model, the outputs of the model can be compared to the data from clinical observation and measures of both normal and pathological hands. For the normal condition the output of the model can be compared to tendon excursions (An and Chao,1979), the equilibrium position of the joint angle (Unpublished data based on the methods described in Ranney et al, 1987) and the dynamic curve of the joint angle versus time (Darling, et al, 1990). The other approach is to change the model structures to mimic the changes seen in the clawed hand and the swan-neck deformity.

RESULT AND DISCUSSION

The final equilibrium joint angles for both the model with (B) and without(A) passive muscle elasticity are listed in Table 1. The results from model B are closer to the cadaver test joint angles than those of model A at the DIP and PIP joints. However, model B is slightly worse at the MP joint. For the MP joint, the passive elastic properties seem to constraint the joint from more flexion or extension. For the PIP joint, when FDP and

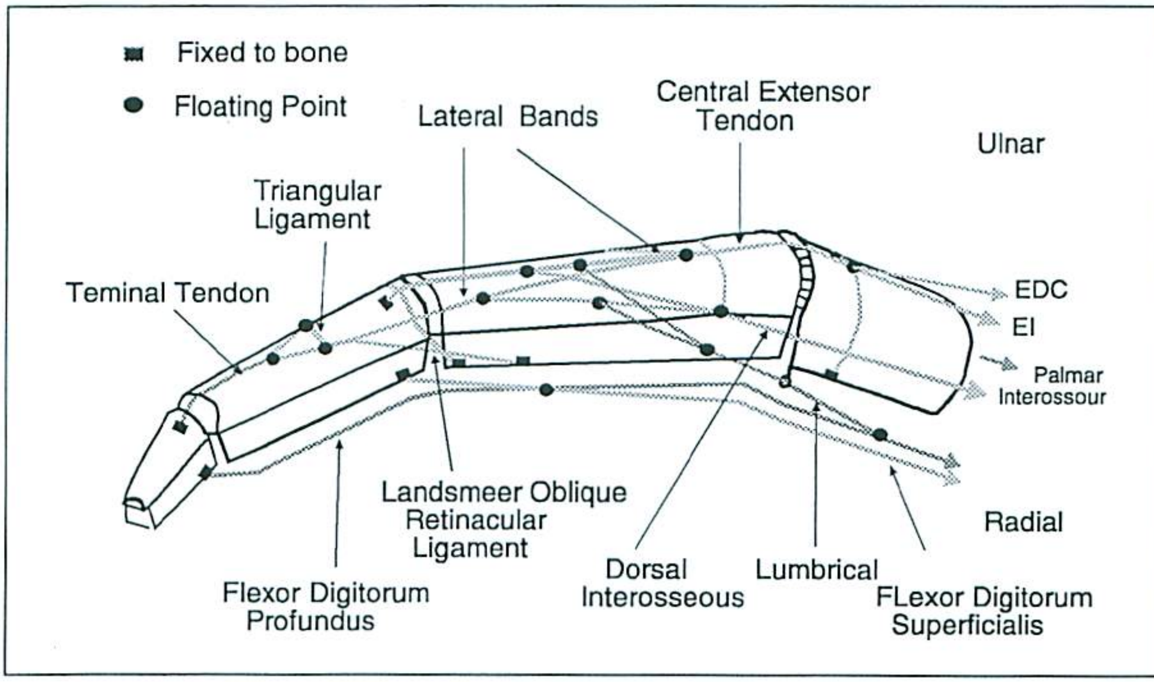

Figure 2. The refined model structure of the index finger.

lateral bands which help the PIP and the DIP joints flex during finger motion. This drives us to refine our model in detail to represent the structure of extension expansion. The refined model is shown in Figure 2. Critical parts of the extensor apparatus include the lateral bands and controlling ligaments and three fibres representing the proximal, middle and edge components of extensor hood. In addition, the MP joint is modelled as a universal joint. It is expected the refined model can predict the finger movement more precisely than the earlier model. Further extensions and uses of this model are planned. For example, this model can be developed to predict the grasp force when the hand holding an object. We believe this model is promising one to allow us to understand the complex relationship of fingers during prehension.

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