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Computer simulation analysis of fracture dislocation of the proximal interphalangeal joint using the finite element method.

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Abstract

Stress is a proximal interphalangeal (PIP) joint model was analyzed by the two-dimensional and three-dimensional finite element methods (FEM) to study the onset mechanisms of the middle phalangeal base fracture. The structural shapes were obtained from sagittally sectioned specimens of the PIP joint for making FEM models. In those models, four different material properties were given corresponding to cortical bone, subchondral bone, cancellous bone and cartilage. Loading conditions were determined by estimating the amount and position of axial pressure added to the middle phalanx. A general finite element program (MARC) was used for computer simulation analysis. The results of the fracture experiments compared with the clinical manifestation of the fractures justify the applicability of the computer simulation models using FEM analysis. The stress distribution changed as the angle of the PIP joint changed. Concentrated stress was found on the volar side of the middle phalangeal base in the hyperextension position, and was found on the dorsal side in the flexion position. In the neutral position, the stress was found on both sides. Axial stress on the middle phalanx causes three different types of fractures (volar, dorsal and both) depending upon the angle of the PIP joint. These results demonstrate that the type of PIP joint fracture dislocation depends on the angle of the joint at the time of injury. The finite element method is one of the most useful methods for analyzing the onset mechanism of fractures.

KEYWORDS: finite element method, stress analysis, computer simulation, fracture experiment, proximal interphalangeal joint, fracture dislocation

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Computer Simulation Analysis of Fracture Dislocation of the Proximal Interphalangeal Joint Using the Finite Element Method

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Stress in a proximal interphalangeal (PIP) joint model was analyzed by the two-dimensional and three-dimensional finite element methods (FEM) to study the onset mechanisms of the middle phalangeal base fracture. The structural shapes were obtained from sagittally sectioned specimens of the PIP joint for making FEM models. In those models, four different material properties were given corresponding to cortical bone, subchondral bone, cancellous bone and cartilage. Loading conditions were determined by estimating the amount and position of axial pressure added to the middle phalanx. A general finite element program (MARC) was used for computer simulation analysis. The results of the fracture experiments compared with the clinical manifestation of the fractures justify the applicability of the computer simulation models using FEM analysis. The stress distribution changed as the angle of the PIP joint changed. Concentrated stress was found on the volar side of the middle phalangeal base in the hyperextension position, and was found on the dorsal side in the flexion position. In the neutral position, the stress was found on both sides. Axial stress on the middle phalanx causes three different types of fractures (volar, dorsal and both) depending upon the angle of the PIP joint. These results demonstrate that the type of PIP joint fracture dislocation depends on the angle of the joint at the time of injury. The finite element method is one of the most useful methods for analyzing the onset mechanism of fractures.

Key words: finite element method, stress analysis, computer simulation, fracture experiment, proximal interphalangeal joint, fracture dislocation

Fracture dislocation of the proximal interphalangeal (PIP) joint, most frequently the middle phalangeal base fracture, is one of the most common and important injuries in the finger joints. Permanent impairment will result if it is not recognized as a severe trauma and treated adequately. Although many papers have been written about this fracture, only Lee (1), Wilson (2), Eaton (3), Bowers (4), Agee (5) and Hastings (6) mentioned briefly its onset mechanism. However, very few studies (7,8) have ever tried to analyze the fracture mechanism. The authors of this study have classified middle phalangeal base fractures into five types (9) that seem to be caused by axial force: dorsal split and dorsal split-depression, volar split and volar split-depression, and so-called Pilon type (10) fractures (Fig. 1).

It is presumed that different positions of the PIP joint yield different fractures under the same direction of force. In this study, the onset mechanisms of these fractures were examined using computer simulation. To analyze stress distribution on PIP joints in several positions within the normal range of movement, two- and three-dimensional finite element methods (FEM) were applied. The results of the FEM analyses were compared with those of experimentally produced fractures to evaluate the validity of these analyses.

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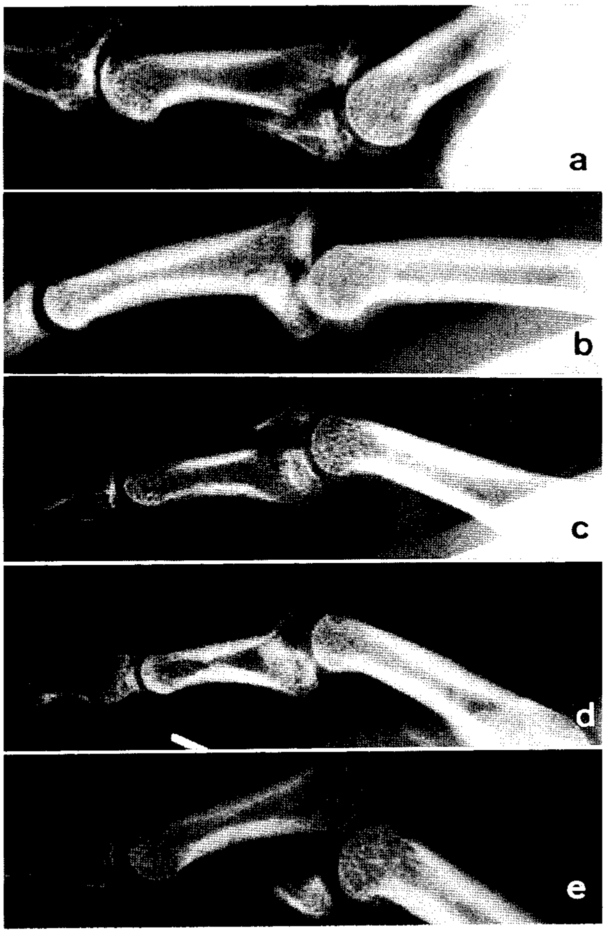

Fig. 1 Clinical manifestation of the fracture dislocation of the proximal interphalangeal joint. a: Volar split type, b: Volar split-depression type, c: Dorsal split type, d: Dorsal split-depression type, e: Pilon type

Materials and Methods

Two distinct groups of subjects contributed the fingers used in these analyses. The members of the first group were patients with malignant tumor of the upper extremity whose disease did not involve the fingers. The surgical amputations were conducted at Okayama University Medical School Hospital between 1988 and 1991. The second group was composed of cadavers that ranged in age from 61 to 93 years (average age 77 years). The method of preservation was uniform for all specimens.

PIP joints taken from amputated fingers of young adults were used to make FEM models. Sagittally

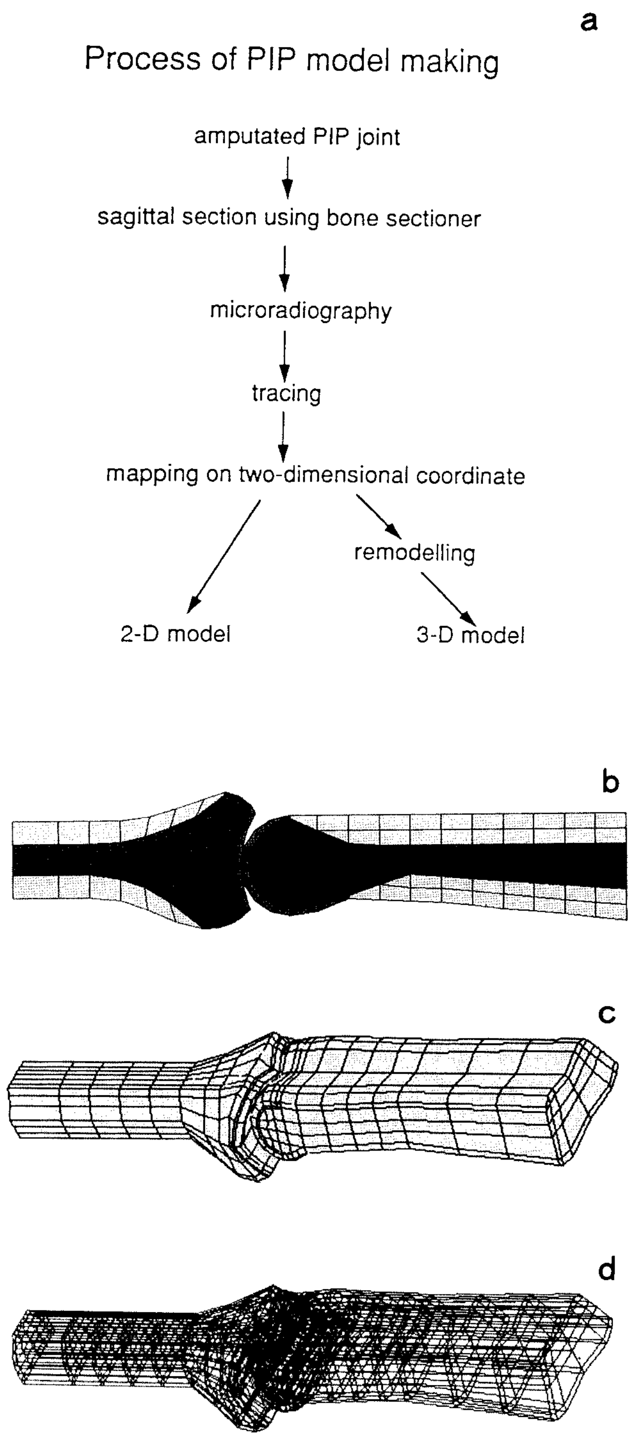

Fig. 2 Proximal interphalangeal (PIP) joint models. a: Process of making PIP model, b: Two-dimensional model, c: Three-dimensional (3-D) model, d: Elements and nodal points of 3-D model.

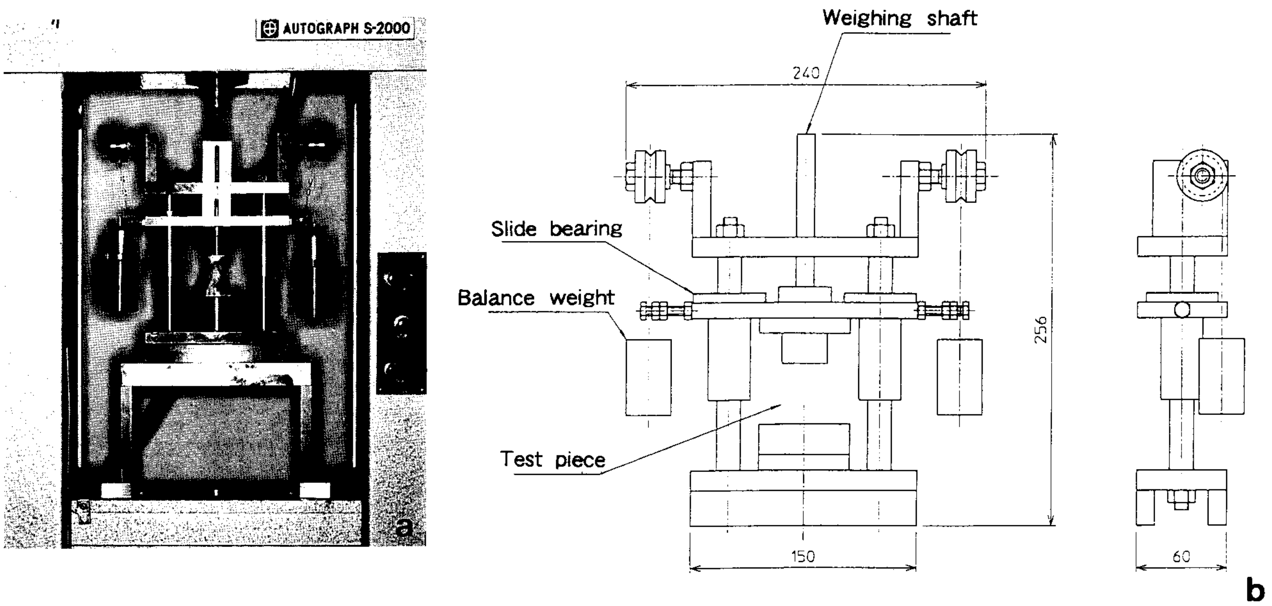

Fig. 3 Experimental study on fracture. **a**: Fracture with the fixator and the loading machine, **b**: Design of the fixator.

sectioned specimens of the PIP joints were made serially at intervals of 1 mm with an EXAKT BS-3000 bone sectioner (Shimadzu Corp. Tokyo, Japan). The microradiography of those specimens was mapped on two-dimensional coordinates. Two-dimensional models were made from serial microradiographic data that included the central and the most prominent part of the condyles. Three-dimensional models were produced using all data serially (Fig. 2a).

The model was divided into four areas according to different properties of four materials; cortical bone, cancellous bone, subchondral bone and cartilage. These material properties were assumed to be linearly elastic and isotropic, and the corresponding numerical values were taken from the literature (11): Young's modulus of cortical bone, subchondral bone, cancellous bone and cartilage was 15,000 MPa, 1,000 MPa, 100 MPa and 5 MPa respectively. Poisson's ratio was 0.3, 0.2, 0.2 and 0.49 respectively. The total number of elements was 180 triangles and quadrilaterals for two-dimensional FEM and 852 hexahedra for three-dimensional FEM. The number of nodes for two-dimensional FEM was 208 and that for three-dimensional FEM was 1246 (Fig. 2b, c).

Axial loads were added to the middle phalanx statically, while the angles of the PIP joints were changed to 22.5° in the hyperextension, 22.5° in the flexion and the neutral positions. Boundary conditions were determined by displacement constraints of the nodal points. Consequently, axial loads (nodal reaction force) were set between 300 and 700 N. Each end of the model was fixed 20 mm from the PIP joint surface. A general finite element program (MARC, MARC Analysis Research Corp. USA) was used for computer simulation analysis of stress distribution. The amount of stress from minimum to maximum force in each condition was divided into 20 levels.

In the experimental fracture study, the PIP joints from 30 cadaveric fingers fixed with 10 % formalin were attached to a fixator of our own design (Fig. 3a) with dental resin. Restricting conditions were set by fixing both ends of the PIP joints at the same angle and depth as those of the computer simulation analysis. Then, axial loads were added statically using the Autograh S-2000 loading machine (Shimadzu Corp. Tokyo, Japan) (Fig. 3). The occurrence of a fracture was determined by changes in the load-deformation curve, which was simultaneously recorded.

Results

Two-dimensional analysis showed that the area of concentration changed according to the angle of the PIP

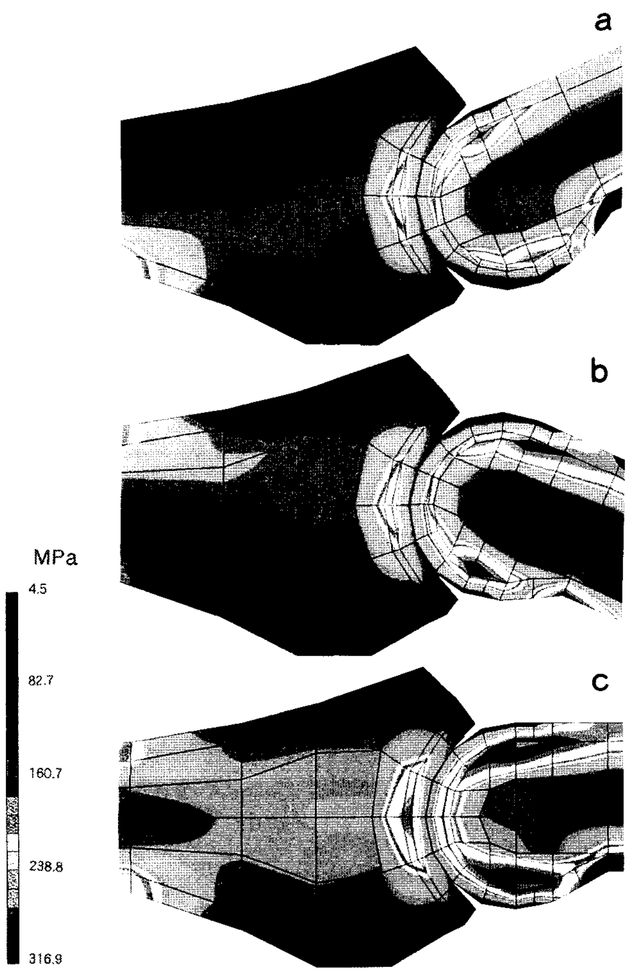

Fig. 4 Stress distribution on two-dimensional model of sagittal section (von Mises stress). **a**: 22.5° hyperextension position, **b**: 22.5° flexion position, **c**: Neutral position

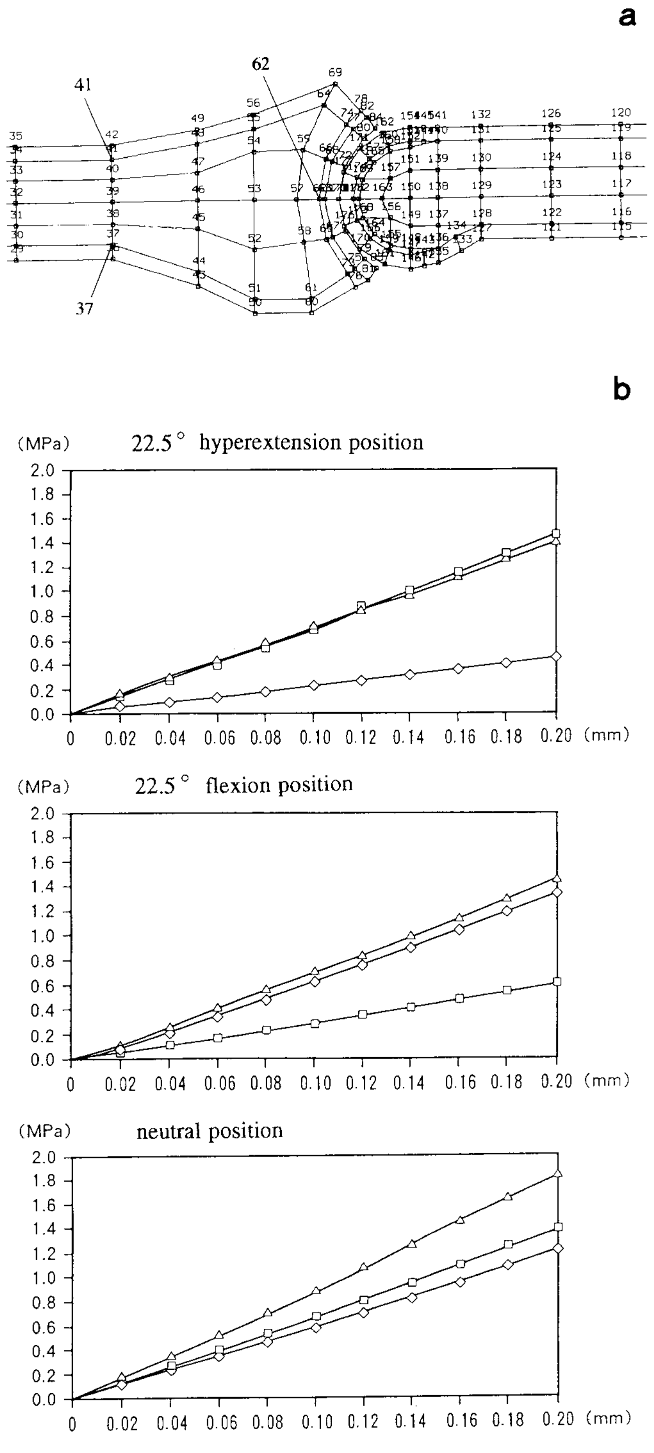

Fig. 5 A model of finite element model. **a**: Nodal labels, Node 37: the most changeable site of stress concentration in hypertension position, Node 41; in flexion position, Node 62; in normal position, **b**: Nodal reaction force of node 37 (□: equivalent von Mises stress), 41 (◇: equivalent von Mises stress) and 62 (△: equivalent von Mises stress)

joints. Stress was found concentrated on the volar side of the middle phalangeal base in the hyperextension position, and on the dorsal side in the flexion position. In the neutral position, stress was found on both sides (Fig. 4). In the hyperextension position, the nodal reaction force of nodes 37 and 62 was similar. In the flexion position, the nodal reaction force of nodes 41 and 62 was similar. In the neutral position, node 62 was the highest. (Fig. 5). In the hyperextension position, axial loading caused not only cartilaginous deformation but also sliding of the proximal phalangeal head to the volar side. In the flexion position, the proximal phalangeal head slid to the dorsal side.

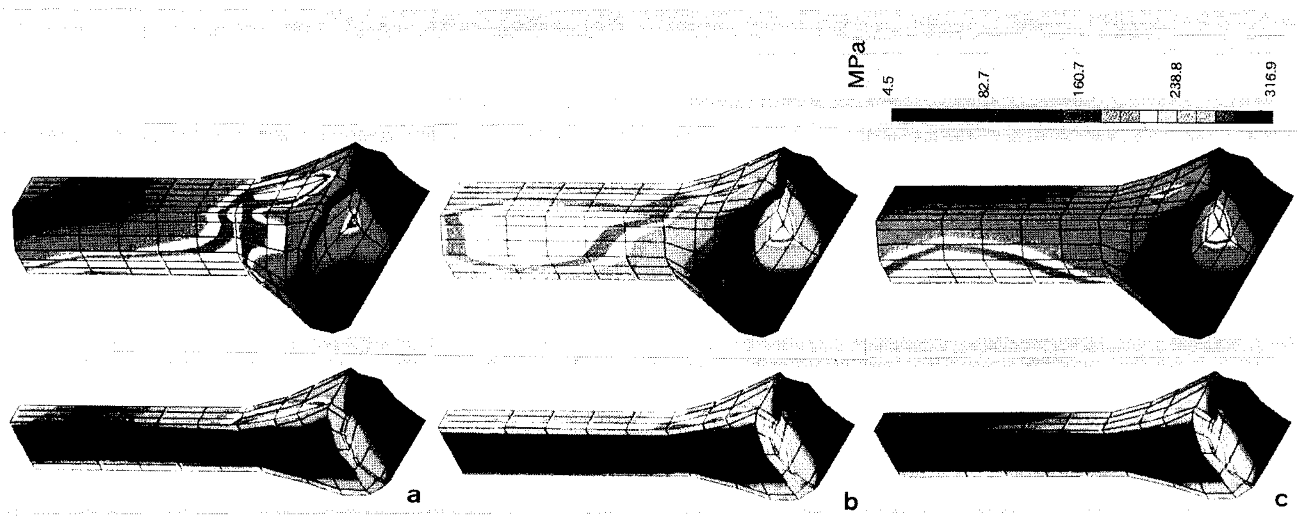

Fig. 6 Stress analysis of three-dimensional models. Stress distribution on the surface (upper) and sagittally sectioned surface (Lower) (von Mises stress). **a**: 22.5° hyperextension position, **b**: 22.5° flexion position, **c**: Neutral position.

Table I Experimental fractures of cadaveric fingers

Position	Forces needed for fractures	Types of injury (number)	Used fingers (number)	Age (average)
22.5° hyperextension position	139.2～947.7 N (541.7 N)	Volar split depression (6) Volar split (2) Volar 2/3 depression (2)	Index (3) Middle (3) Ring (4)	18～82 years (68.3)
22.5° flexion position	388.1～882.0 N (604.6 N)	Dorsal split depression (9) Dorsal 2/3 depression (1)	Index (3) Middle (3) Ring (4)	23～82 years (66.8)
Neutral position	176.4～899.6 N (578.4 N)	Dorsal 2/3 depression (3) Dorsal split (4) Central depression (1) Volar split (2)	Index (2) Middle (1) Ring (3) Little (4)	18～93 years (62.5)

Three-dimensional analysis also showed superficially concentrated stress on the dorsal and volar aspect of the middle and proximal phalanx in the hyperextension, flexion and neutral positions. Concentrated stress changed according to the position of the PIP joint in almost the same manner as in the two-dimensional FEM analysis. An image of the stress distribution on the articular surface of the middle phalangeal base after removal of the proximal phalangeal head was displayed on the computer. There was no concentrated stress on the articular cartilage. In the view of the sagittally cut surface of the central position, stress was concentrated in the subchondral bone area. Stress was concentrated in the volar area in the hyperextension position, and in the flexion position, it shifted dorsally. In the neutral position, stress was observed in both areas (Fig. 6). The area of stress distribution was similar to the results of two-dimensional analysis.

The fracture area of the middle phalangeal base, the load at fracture, age and finger used for each specimen in each position are shown in Table 1. Volar split and/or depression fractures occurred in the hyperextension position, dorsal split and/or depression fractures in the

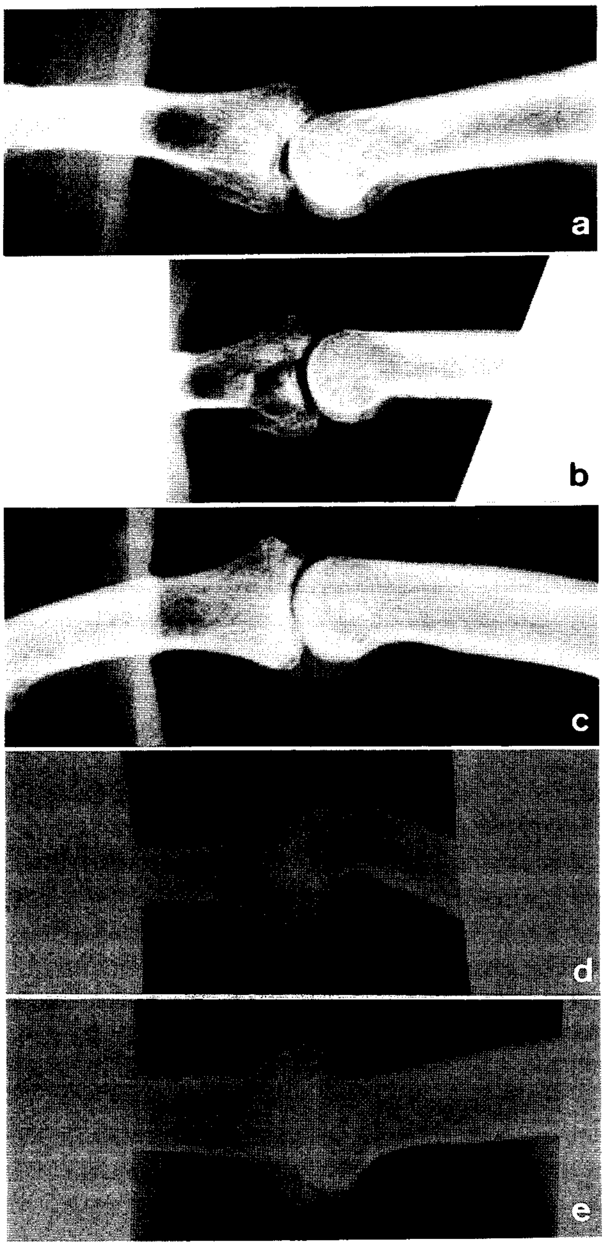

Fig. 7 Experimentally produced fractures. **a**: Volar split type, **b**: Volar split-depression type, **c**: Dorsal split type, **d**: Dorsal split-depression type, **e**: Central depression type

flexion position, and central depression type fractures in the neutral position. More specifically a volar split-depression type fracture occurred in six cases, a volar split type in two cases, and depression fragment on the volar 2/3 area in two cases in the hyperextension position. In the flexion position, a dorsal split-depression type fracture occurred in nine cases, and depression fragment on the dorsal 2/3 area in one case. In the neutral position, depression fragment occurred on the dorsal 2/3 area in three cases, a dorsal split type fracture in four cases, a central-depression type in one case, and a volar split type in two cases (Fig. 7 and Table 1).

Discussion

The onset mechanism of fracture dislocation of the PIP joint is still obscure. Analysis of stress distribution on the PIP joint may be the key to the clarification of that mechanism. The FEM provides a reliable general program, an engineering-approximate solution between theory and practice. As long as we can make a numerical model that is nearly identical to the subject material and use reliable data, we can expect to obtain good results instantly (12). Although FEM has been applied successfully in biomechanical studies in the field of orthopaedic surgery (13, 14), the range of established theoretical numerical values of the properties of biomaterials is limited. More detailed three-dimensional models are needed.

There are several methods for making an identical model. In the indirect method, the data of structural shapes that are obtained from computed tomography (CT) of the bone are put into the computer. In the direct method, structural data are directly put into the computer with a non-contact three-dimensional digitizer. It is impossible to make a three-dimensional model using only radiographical data of the bone because numerous three-dimensional coordinates are required. These direct methods of analysis are unsuitable because the components of the PIP joint are too small to be scanned at 1 mm intervals or for a strain gauge to measure.

An accurate three-dimensional model can be obtained with a non-contact three-dimensional digitizer. However, when we analyze the stress distribution on a joint to get a realistic result, it is more important to use a complex material model that includes all of the structural elements of the joint (cortical bone, subchondral bone, cancellous bone and cartilage) than to use a single material model (15). The digitizer alone could not provide digital images of the internal structures of the bone. Therefore, we made two- and three-dimensional models with data from sectioned PIP joints to model both external and internal structural elements.

Theoretical numerical values of material properties for analysis were taken from the literature (11), and assumed to be linearly elastic and isotropic, like metallic substances. However, the actual material properties of organic substances like bone and cartilage are nonlinear and anisotropic. Dynamic, nonlinear and anisotropic analysis would be more appropriate, but this type of analysis still requires substantial, expensive technological and theoretical development.

Until now, stress transmission between two objects has been analyzed mainly by two-dimensional FEM and occasionally by semi-three-dimensional FEM using the side-plate theory (16). The validity of our simulation was tested by comparing the area of stress concentration in each PIP joint position in the model with the fractured area in the experimental fracture study.

Stress analysis using FEM models showed that the concentrated stress distribution area changed according to the angle of the PIP joint. In the hyperextension position, concentrated stress was predicted on the volar side of the middle phalangeal base, and on the dorsal side in the flexion position. In the neutral position, it was predicted on both sides. In the experiments using cadaveric fingers, the fracture area of the middle phalangeal base was almost the same in each position and the results of the fracture experiments corresponded well with the computer simulation analyses. The reason the same fracture did not always occur at the same angle of the PIP joint is thought to be due to differences in individual joints. The qualitative results of FEM were in complete agreement with those of the fracture experiments despite the arbitrary assumptions regarding material properties. These results support the validity of the model (17).

We compared the results of computer analysis and fracture experiments with a clinical classification developed in 1989 (9). We found it possible to make similar fractures in the experiments using cadarveric fingers, and predicted fracture patterns based on the computer simulations. Fracture areas were almost identical to the areas of stress concentration seen in the computer simulation, thus confirming our predictions. From this we may conclude that forces on the finger-tips are transmitted to the distal phalanx and then to the middle phalanx. When the interphalangeal joints are locked in the swan-neck position, the PIP joints enter the hyperextension position, causing volar split and volar split-depression type fractures. However, when the interphalangeal joints are locked in the buttonhole position, the PIP joints enter the flexion position, which produces dorsal split and dorsal split-depression type fractures. Near the neutral position, axial forces make split depression fractures and impacted forces in the completely neutral position may produce Pilon type fractures of the middle phalangeal base.

Dorsal type and Pilon type (10) fractures are presented less often than the volar type (9). We presume that the position of the PIP joint at the time of injury is responsible for the different incidences of these fractures. An axial load that maintains a particular flexion angle of the joint is very unlikely because in the flexion position an axial load can be converted to a bending force which flexes the PIP joint further. The neutral position of the PIP joint under axial loading is also very unstable, and is easily converted to the flexion or hyperextension position. In contrast, an axial load can be continuously added in the hyperextension position because this position is stable due to the resistance of the volar plate, within certain limits. Therefore, this fracture type is most likely to occur.

Although this preliminary study is qualitative, FEM analysis combined with the study of experimentally produced fractures appears to be useful for the identification of the onset mechanism of these fractures. Future studies must address several issues: a) Methods to produce more accurate models of the shapes of the joint components must be developed, b) more data on the uniformity and continuity of biomaterial properties are needed, and c) new and refined algorithms are required to create FEM models that can simulate the union of the very different materials that are in contact in implants and grafts. The techniques, relative merits, and applications of shell models and solid models for this kind of FEM analysis should be a fruitful area of research.

Axial stress on the middle phalanx produces three different fractures, volar, dorsal and a combination of both, depending upon the angle of the PIP joint at the time of fracture. The combination of fracture type and PIP joint angle could be predicted from the FEM simulation results. Stress distribution changed as the angles of the PIP joint changed. In the hyperextension position, stress was concentrated on the volar side of the middle phalangeal base, and on the dorsal side in the flexion position. In the neutral position, stress was concentrated on both sides.

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