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Numerical Analysis of the Lamb Metacarpal Bone: Approximation of Bending Tests

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ABSTRACT

In the development of new strategies for fracture fixation, new methods have to be tested biomechanically under in vitro conditions before clinical trials can be performed. Several studies, including tensile, compressive, and bending tests for fresh whole bone specimens, offer the possibility to understand animal bones mechanical behavior. Therefore, in the present study three point bending tests were applied on the lamb metacarpal bones at different speeds and determine the mechanical properties of bone. For the experiments 12 specimens were obtained from 1 year old Ankara curly lambs and three point bending tests were conducted using three different bending speeds to assess and compare bone fracture properties. From the test results strains, deformations and stresses were calculated for three different bending compression speeds. Finite Element Analysis results were compared to the test results. Because of the use fresh bone specimens of an animal part are used like in vivo tests in biomechanical studies, investigating failure loads of the metacarpus by bending tests and numerical analysis are guiding for clinical operations and computer simulations.

Keywords: Finite element analysis, bending test, lamb metacarpal bone, biomechanics

1. INTRODUCTION

There has been a considerable interest in the measurement of the mechanical properties of animal bones. Animal models, offer the possibility of naturally achieving or genetically engineering a skeletal phenotype and conducting destructive fracture tests on bone to determine the resulting change in bone's mechanical properties [1].

In recent years, new concepts and implants for the treatment of fractures in bone mechanics have been developed. Before clinical trials, laboratory evaluation of these new concepts and implants by means of biomechanical in vitro experiments is required. The in vitro experiments should mimic in vivo conditions as closely as possible. Therefore, the standard is the use of fresh-frozen specimens, as the mechanical properties of bone are not altered significantly by freezing [2–7]. However, one disadvantage of fresh-frozen specimens is the remaining risk of contamination with pathogenic germs. Furthermore, long-duration tests at room temperature are hardly possible because of the rapid deterioration of nonembalmed specimen [2,8]. In addition, most human tissue available for biomechanical in vitro testing is derived from anatomical departments and is stored in various preservation solutions. This leads to a limited

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availability of fresh-frozen specimens, as fresh-frozen storage is more costly. For these reasons, biomechanical in vitro tests are frequently conducted using specimens treated with different chemical preservation methods. However, it is controversially discussed in the literature whether and how different preservation methods affect the mechanical properties of bone [2]. In the present study to avoid this kind of preservation and storage problems and not to affect the mechanical properties of bone, metacarpal bones were not subjected to any application.

In the study of engineering mechanics and materials, the theory of fracture mechanics and related experimentation has proven to be strength-based methods like tensile, compression and bending tests are the fundamental test methods of engineering. For determining properties of bone, mechanical tests were carried out in the literature [1].

In particular, similar to a three point bending test on unnotched whole bone, the fracture toughness test of a whole bone that is notched and subjected to crack initiation and propagation under tensile mode requires that bone has a straight morphology with a uniformly round and thick cross-section. Using the above criterion, and testing different long bones from skeletons of mice, Schriefer et al. [9] found that Mouse radius produced accurate and most consistent results [1]. For three-point bending tests of single trabeculae and imaging with high-speed photography, Thurner et al. used a custom-made mechanical testing device previously described in detail [10,11]. Constantinos et al. was subjected each metacarpal bone to a three-point bending test until failure, using a materials testing machine (Karl Frank GmbH, Weinheim). Each specimen was positioned horizontally on the two holding fixtures of the machine, with the metacarpal bone tuberosity facing outwards, while the upper loading fixture applied the load from lateral to medial at a loading rate of 0.4mm/min [12].

To simplify and support mechanical test methods, Finite Element Analysis (FEA) is a commonly used tool in biomechanics research for prediction of the mechanical competence of bone structures [10, 13, 14, 15, 16].

The aim of the present study was to determine the mechanical properties of recent slaughtered lambs' freshly dissected metacarpal bone specimens by the destructive 3-point bending tests with three different compression speeds. 3-point bending results for different speeds were compared each other and to the computer aided finite element analyzes for three samples.

2. MATERIALS AND METHOD

To determine metacarpal bone mechanical behaviors 3-point bending test and FEA were carried out in several experimental studies. Some of these studies have been performed to determine the material properties and force–deformation behaviors of the bone tissues under three-point bending or tensile loading [17, 18, 19, 20, 21, 22, 23, 24, 25].

2.1. Specimens

In this study 12 Metacarpal bone specimens obtained from 1 year old Ankara curly lambs, cleaned from all soft tissue, were obtained from a local abattoir at Karasu, Sakarya, TURKEY. See Fig. 1 for selected metacarpal bones.

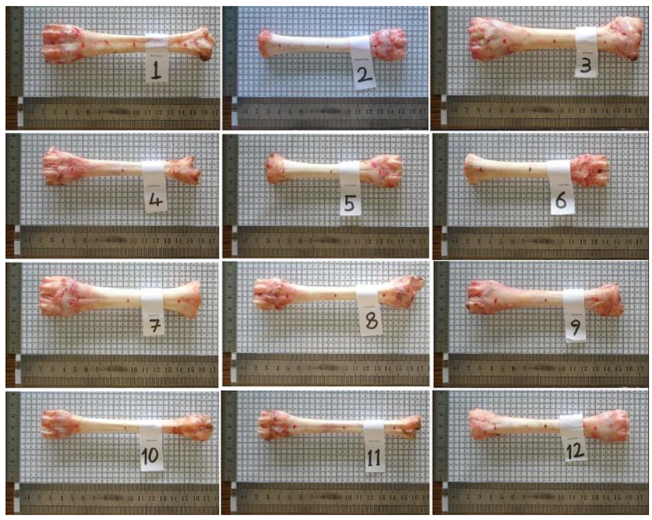

Figure 1. 12 Metacarpal bone specimens obtained from 1 year old Ankara curly lambs, cleaned from all soft tissue, were obtained from a local abattoir at Karasu, Sakarya, TURKEY.

To make easy calculations, CAD and Finite Element Model (FEM), cross section of the bones were taken elliptic (For anterior and lateral diameters). Anterior and lateral diameters of metacarpal bones were measured. In the Fig. 2, the description of dimensions of metacarpal bone was belonging to the proximal sides to the middle and to the distal sides.

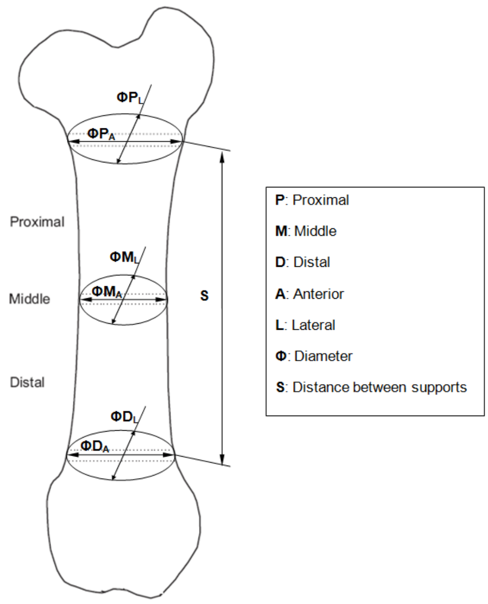

Figure 2. The measurements of metacarpal bone were belonging to the proximal sides to the middle and to the distal sides.

Proximal and the distal sides of metacarpal bone were selected for the first and second support and the middle section was considered for the plunger of the test machine. See Table 1 for the dimensions of 12 metacarpal bones.

Table 1. Dimensions of the 12 metacarpal bones of the 1 year old Ankara curly lambs.

Bending Speed (mm/s)	**Bone Diameters (mm)**						
	Bone Number	Proximal Diameter (Lateral)	Proximal Diameter (Anterior)	Middle Diameter (Lateral)	Middle Diameter (Anterior)	Distal Diameter (Lateral)	Distal Diameter (Anterior)
0.5mm/s	**1**	15,1	23	13,3	19,55	18,1	17,7
	2	11,2	15,1	9,5	11,4	12,8	19,1
	3	17,53	28,1	13,6	16,1	16,1	20,1
	4	14,55	23,7	11,8	12,1	16,53	15,54
4mm/s	**5**	14,8	17,2	10,1	12,9	15,2	26,8
	6	13,2	19,2	9,4	13	13,8	24,1
	7	15	26,3	11,6	15,4	16	20,5
	8	11,8	18,8	11	12,3	17,9	16
20mm/s	**9**	13,7	24,8	9,7	13,4	14,5	18,2
	10	11,8	15,4	10,6	10,8	13,7	13,1
	11	11,4	15,7	10,4	10,7	13,5	13,2
	12	12,6	17,3	9,8	11	13	19

2.2. Bending test protocol

Three-point bending tests were performed on each metacarpal bone using a custom testing machine (Servo hydraulic press with 400mm stroke and 40 ton cylinder pressure; 5000 N load cell capacity). See Fig. 3 for the 3-point testing machine setup. Distance between supports was 83mm. Plunger speeds were adjusted to 0.5mm/s, 4mm/s and 20mm/s. For each plunger speed, four bones were subjected to 3-point bending tests.

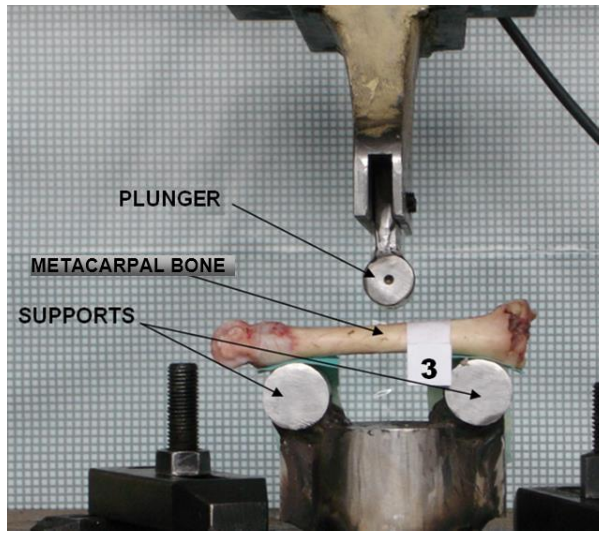

Figure 3. 3-point bending test setup.

2.3. Modeling and analysis

The computational tests consisted of creating finite element models of elliptical metacarpal bones under three-point bending. Support width was arbitrarily set to 83 mm. The models consisted of eight-node, higher-order and arbitrarily distorted elements. Element size was selected such as to provide a smooth mesh. The models were transferred by Pro_ENGINEER and solved using ANSYS Classic and were used to calculate prescribed displacements in the tests needed to obtain the stresses and strains (Fig. 4). The analyses were repeated for other samples.

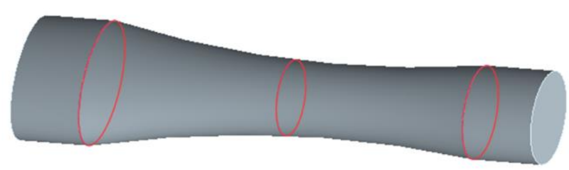

Figure 4. Basic CAD model of metacarpal bone.

Metacarpal bone 3, 7 and 9 were modeled simply as varying elliptic sections. The plunger contact point on top of the modeled metacarpal bone was displaced in the y-direction (down) until fraction; this displacement corresponds to the experimental plunger displacement prior to the failure point of the specimen. The two supporting points at the bottom were modeled as hinges, which allow free rotation around the z-axis (out of the image plane) but define a non-slip fixed boundary condition in the x- and the y-direction. The metacarpal bones were half symmetrically modeled by the XY plane. See Fig.5a for the CAD model and Fig.5b for FEA model.

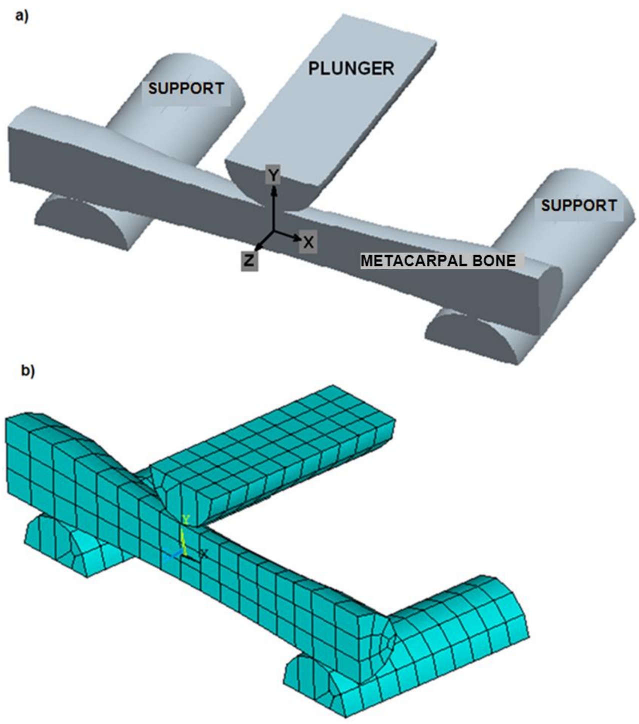

Figure 5: Computer Aided Simulation models of 3-point bending test (a. CAD model, b. FEA model).

Although bone material model is not isotropic and lineer for a simple and easy approach, the FEA of bone model is based on a linear elastic material model (linear static analysis) and bone was assumed as an isotropic material with a density of 1.9g/cm^3, an elastic modulus of 2.0GPa, and a Poisson's ratio of 0.3 as used in the references [10, 26]. The properties of metacarpal bone was not calculated from the tests but taken from the literature. Finite Element Simulations were figured out under static conditions by giving displacement to the plunger. The displacement values were taken from the 3-point bending tests of each selected metacarpal bones (metacarpal bone 3, 7 and 9) between the plunger contact point and the metacarpal bone fraction point (Max. Force).

3. RESULTS AND DISCUSSION

3.1. Evaluation of results

The mechanical properties of metacarpal bone specimens were determined in a destructive 3-point bending test to investigate the influence of three different compression speeds as 0.5mm/s, 4mm/s and 20mm/s and to compare them to the static Finite Element Analysis of representative metacarpal bones for each compression speed group. With the help of load cell, reaction forces of metacarpal bones and displacements are recorded by the computer. Force - Displacement curves of metacarpal bones for 0.5mm/s, 4mm/s and 20mm/s were respectively shown in Fig.6, 7 and 8.

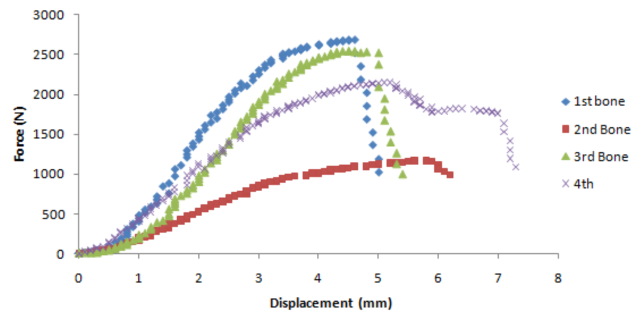

Figure 6. Force-displacement curve of metacarp. bones at speed of 0.5mm/s.

In Fig.6 because of the dimensions of metacarpal bone 1 and 3 were closer, reaction forces were exactly the same. Metacarpal bone 4 was a slender bone and reaction force less when it was compared with 1 and 3. The thin metacarpal bone in first group (plunger speed of 0.5mm/s) when the dimensions were considered was metacarpal bone 2. Such as the dimensions of the bone, reaction force distribution was in the same manner. Like in Fig. 6, a slender bone decreases the cross-sectional moments of inertia and the reaction forces of metacarpal bones (Fig. 7 and 8).

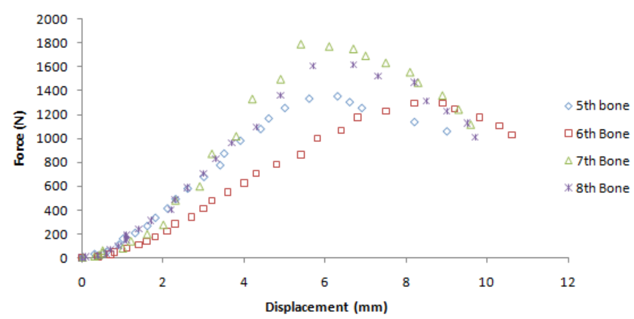

Figure 7. Force-displacement curve of metacarp. bones at speed of 4mm/s.

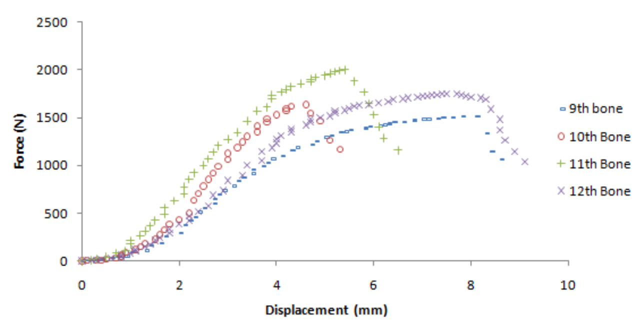

Figure 8. Force-displacement curve of metacarp. bones at speed of 20mm/s.

Strongest metacarpal bone for the second group (plunger speed of 4mm/s) was seventh and the weak one was sixth bone. For the third group (plunger speed of 20mm/s), eleventh metacarpal bone was strongest, ninth metacarpal bone was the weakest bone. The results of maximum reaction forces and displacements for 12 metacarpal bones were shown in Table 2. When the forces and displacements were evaluated, varying results were determined. To calculate the X axis stresses of the test results (Table 2), the mean cross sectional area moments were calculated from the medial elliptical zone of the metacarpal bones.

Table 2. Maximum reaction force and displacement results for 12 metacarpal bones.

Bone Number	**Test Results**			**Medial Cross Sectional Moments of Inertia; I_z (mm^4)**
	Max. Reaction Force (N)	**Displacement (mm)**	**Max. X Stresses (N)**	
1	2687.94	4.6	657.458	2256.583
2	1167.39	5.8	959.759	479.5406
3	2550.6	4.6	724.498	1986.974
4	2118.96	5.3	1063.829	975.3962
5	1353.78	6.3	870.190	652.0839
6	1294.92	8.9	953.547	529.7569
7	1795.23	5.4	732.794	1179.354
8	1618.65	6.7	919.943	803.2169
9	1510.74	8.1	1013.538	600.0255
10	1638.27	4.6	1141.953	631.0896
11	2001.24	5.4	1462.673	590.5184
12	1746.18	7.7	1398.114	507.9496

Analysis of variance in speeds and reaction forces showed that there were significant regional differences in metacarpal bone, but only in fundamental mechanical behavior effects of cross-sectional moments of inertia of metacarpal bones. There was also a correlation between reaction forces of the metacarpal bones up to its own cross sectional moments of inertias in each plunger speed group. Precise comparisons could not be figured out between the metacarpal bones which were tested in three different speeds.

To understand the relationship between the bending tests and FEA, the three different computational models, chosen from each plunger speed group (metacarpal bone 3, 7 and 9), were solved in ANSYS with statically structural analysis conditions. Von Misses stress distribution of metacarpal bone 3 sample was shown to determine the critical areas (Fig. 9). Further detailed evaluation normal compressive and tensile stresses and strains at X axis (metacarpal bone elliptic center) should be evaluated (Table 3).

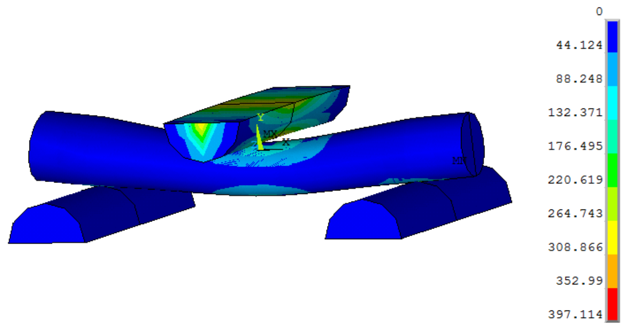

Figure 9.Von Misses stress distribution of metacarp. bone3.

Table 3. Finite Element Analysis results for destruction point of the representative metacarpal bones for each speed.

Bone Number / (Plunger Speed)	**Max. X Comp. Stresses (MPa)**	**Max. X Tensile Stresses (MPa)**	**Max. X Comp. Strain (%)**	**Max. X Tensile Strain (%)**	**Max. Von Misses Stresses (MPa)**	**Max. Von Misses Strain (%)**
3 / (0.5mm/s)	194.867	109.155	0.0946	0.0538	397.114	0.1534
7 / (4mm/s)	189.418	110.462	0.0902	0.0537	321.66	0.1152
9 / (20mm/s)	247.542	149.159	0.1058	0.0726	372.339	0.1895

When the test results and Finite Element Analysis were compared, significant differences were observed. The observation of the results was helped to figure out that the differences were derived from the perfect FEA models, static simulation conditions and the material model properties which were taken from the literature. However some other new bone studies help us how to navigate continuously [26-28]. Naturally, metacarpal bone structures are not standard. Thus, similar size metacarpal bones could be treated differently. For perfect elliptical FEA models and material model properties, mean standard deviation value was generated. The correction factors were empirically derived and applied to account for computational model overestimation of bone stresses (Table 4).

Table 4.Correction factors for FEA results of stresses of metacarpal bones for each plunger speed group

Bone Number	Correction Factor	
	Max. X Comp. Stresses	Max. Von Misses Stresses
3	3.71	1.82
7	3.86	2.27
9	4.09	2.72

These results indicate that bending test solution of lamb metacarpal bone is only appropriate with the correction factors for specimens under computational biomechanical studies for the accepted material properties given in the literature [10, 29].

4. CONCLUSIONS

The present study investigated the changes in forces and stresses of the twelve different metacarpal bones in 3-point bending tests in different plunger speeds and also determined the behavior of metacarpals under FEA conditions. For further reliable and simple Finite Element Analysis of biomechanical applications of different metacarpal bones about observed speeds and used properties, correction factors were generated.

The results of the present study suggest that in biomechanical studies investigating failure loads of metacarpal bones under bending simulations, appropriate correction factor should be used. The use of correction factor is enabled simple computer simulations about biomechanical applications without making pilot tests.

Because of the use fresh bone specimens of the Ankara curly lambs are used like in vivo tests in biomechanical studies, investigating failure loads of metacarpal bone by bending tests and numerical analysis are guiding for clinical operations, biomechanical tests and computer simulations.

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