Experimental Investigation on Fatigue Evaluation of Orthopaedic Locking Compression Plate

Saenoddin Mohajerzadeh, Khalil Farhangdoost*, Pedram Zamani, Kamal Kolasangiani
Department of Mechanical Engineering,
Ferdowsi University of Mashhad, Mashhad, Iran
E-mail: Saen.mohajerzadeh@gmail.com, Farhang@um.ac.ir*,
P.zamani@mail.um.ac.ir, Kamal.kolasangiani@gmail.com
*Corresponding author

Received: 23 June 2018, Revised: 30 August 2018, Accepted: 17 December 2018

Abstract: Locking compression plate (LCP) is a common orthopedic instrument for internal fixation and healing of bone trauma. It is important to study on mechanical behavior and failure investigation of LCP because its failure leads to lots of cost and pain to the patient. In this paper, fatigue life of an eight-hole tibia LCP is evaluated under flexural loading. A four-point bending jig is manufactured and fatigue tests are performed for different compression loads. Fatigue life cycles are investigated for compression loads of 500, 600, 700, 800, 900 and 1000 N and relation between compression load and life cycles is estimated. 125 walking days is estimated for the patient during treatment period according to life cycle results. Post failure analysis results on fracture surface revealed that the crack initiated from the edge of compression hole and propagated from lower to the upper surface of LCP according to beach marks. Finally, Scanning electron microscopy (SEM) on the fracture surface revealed striations as a proof of fatigue crack growth. The striation spacing near the crack initiation site is found to be smaller than this spacing far from the initiation zone. The fatigue crack propagation life is estimated as 1600 cycles according to the number of striation spacings.

Keywords: Failure Analysis, Fatigue Life, Four-Point Bending, Locking Compression Plate, Striation Spacing

Reference: Mohajerzadeh, S., Farhangdoost, K., Zamani P., and Kolasangiani, K., "Experimental Investigation on Fatigue Evaluation of Orthopaedic Locking Compression Plate", Int J of Advanced Design and Manufacturing Technology, Vol. 11/No. 4, 2018, pp. 47–52.

Biographical notes: Saenoddin Mohajerzadeh is an MSc student in Mechanical Engineering and he has technical background in manufacturing orthopaedic instruments such as locking compression plates. **Khalil Farhangdoost** is Professor of Mechanical engineering at the Ferdowsi University of Mashhad, Iran. He received his PhD in Mechanical engineering from McGill University of Canada. His current research focuses on fatigue, fracture of engineering materials. **Pedram Zamani** is PhD candidate at Ferdowsi University of Mashhad, Iran. He received his MSc degree from Ferdowsi University of Mashhad, Iran. His research interests include fatigue life estimation and damage analysis of adhesive joints and orthopaedic instruments. **Kamal Kolasangiani** is PhD Candidate at Ferdowsi University of Mashhad, Iran. He received MSc degree from Shahrood University of Technology. His research interests include the study on ratcheting phenomena and fatigue testing.

1 INTRODUCTION

Tibia bone fracture is one of the most common traumas that is caused due to auto-vehicle accidents [1-3]. Internal and external fixators are widely used to cure critical bone fractures. Compression plates are common orthopedic devices that are applied in orthopedic surgery. These plates are categorized into dynamic compression plate (DCP) and the locking compression plate (LCP). DCP is compressed to the bone surface by means of tightened screws. According to compressive force at the interface of DCP and bone, osteoporosis may cause due to the poor blood supply to the bone surface. The advantage of LCP is that vascular supply is retained because of a gap between bone and plate. LCPs also help in accelerating treatment by decreasing tensile stress, increasing compressive stress and fixing the fractured surface [4], [5]. According to continuous and periodic loading on LCPs during the orthopaedic treatment procedure, it is important to study on mechanical behavior and life estimation of these orthopaedic instruments under cyclic loading condition. Failure of a locking compression plate (LCP) may cause serious trauma for the patient and leads to lots of pain for him. Thus, it is very important to study the mechanical behavior of LCPs and to prevent their failure.

2 LITERATURE REVIEW

Over the last decade, numerous research works have been performed to study the mechanical behavior of the LCP in order to prevent its failure and drastic damage to the patient. Snow et al. [6] studied on the benefit of locking compression plate (LCP) in compare with dynamic compression plate (DCP). The results of their study showed that the LCP is mechanically superior to the DCP. Kanchanomai et al. [7] performed an experimental evaluation on fatigue failure of femoral locking compression plate (LCP). They observed that the first fatigue crack initiated at a subsurface position under the surface of compression hole and another crack is found to be initiated from the surface of the locking hole. These two cracks propagated through the depth of LCP and fatigue life is estimated according to striations. Okazaki [8] compared the fatigue strength crack growth rate for different orthopedic metals. He revealed that the amount of stress intensity factor range for stainless steel and Co-Cr-Mo-Ni-Fe alloy are more than Ti alloy. Gervais et al. [9] carried out an investigation of fatigue failure and crack initiation of 316L stainless steel and concluded that bending stresses are the cause of crack initiation and growth. Stability analysis of DCP and LCP implants in correcting varus deformity of the knee was accomplished by Izaham et al. [10]. They modeled Tibia from computed tomography images and simulated fixation models. They showed that locking compression plates have better stability than DCPs for fixation in the high tibial osteotomy. Nassiri et al. [11] performed a finite element analysis of a transverse long bone fracture that was fixed with a LCP. They illustrated that the maximum Von Mises stresses were happened in the deepest screws at the screw-head intersection. Marcomini et al. [12] analyzed the failure of a femoral LCP and presented that the poor material quality was the main reason for fracture. They observed that the chemical composition of material was not in accordance to the standards and concluded that the fracture was a result of brittle crack initiation, separation at grain boundaries, crack propagation and its unstable growth. Sepehri et al. [13] applied finite element method to analyze different screw arrangements in 11-hole LCP in order to investigate the stresses on the bone surface, plate and screws. They also considered variation in bone properties during 16-week time span. A numerical analysis was conducted by Zhang et al. [14] to study the effect of plate-bone distance on the stability of external plate fixation. Their results revealed that the plate-bone distance should be less than 30 mm to achieve stable fixation in a distal tibial fracture. Shaat [15] obtained the fatigue properties of femoral and tibial LCPs by considering knee biomechanics during walking. He reported the fatigue safety factors as a function of body weight and bone fracture location on the basis of the knee joint's biomechanics.

Previous research works investigated on comparing strength and stability of dynamic and locking compression plates, the effect of alloy composition on fatigue and fracture of femoral LCPs according to their fixation in the body. In other researches, the finite element analysis was implemented to study the stress distribution in holes and screws, screw arrangements in 11-hole LCP and to check the effect of different plate-bone distances on the stability of external fixation. According to the curvature of Tibia LCPs and the applied load to their ends, bending is a dominant loading which is applied to LCPs during physiotherapy exercises. In this paper, a four-point bending jig is manufactured in order to experimentally evaluate fatigue life of eight-hole Tibia LCP (316L steel). Fatigue life cycles are achieved for different compression loads and physiotherapy gait cycles are estimated for a fail-safe usage of LCP. The post-failure analysis is performed according to optical and scanning electronic microscopy (SEM) to detect the crack initiation site and crack growth direction. Finally, Fatigue propagation life cycles are estimated according to striation spacings.

3 PROCEDURE FOR PAPER SUBMISSION

3.1. Materials and Methods

Eight-hole LCP (12 mm width and 180 mm Length) made from 316L steel was selected for the present research. Test specimens were manufactured after cutting, forging and machining according to ASTM F621-02 [16]. Section of the LCP was polished and etched for 20 seconds using electro-polish method (Struers Lectropol-5 machine) by means of a liquid that was prepared by mixing 5 g of oxalic acid and 50 mL distilled water in order to show the microstructure of the material. Austenitic phase was observed as the microstructure of LCP ("Fig. 1"). The presence of manufacturing defects and poor material quality is a cause of failure in metals [12], [17]. Therefore, the chemical composition of the LCP was measured by emission spectrometry according to ASTM E1086-05 [18] ("Table 1"). The chemical composition was found to be in accordance with the ASTM F138 standard [19]. The hardness of 295 HV was measured for the LCP.

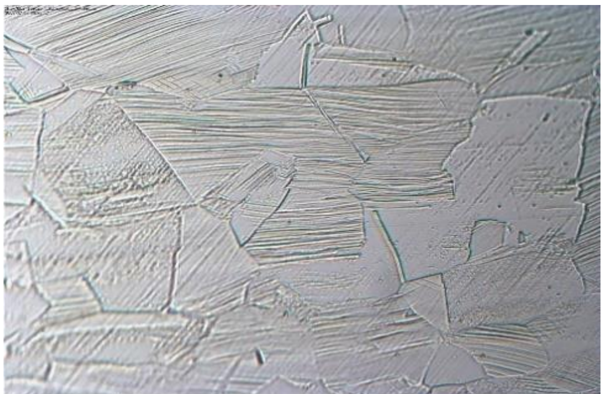

Fig. 1 The austenitic microstructure of LCP.

Table 1 Chemical composition of the LCP

Elements	LCP	ASTM F138 Requirement
C	0.030	≤ 030
Si	0.460	≤ 0.750
Mn	1.439	≤ 2.00
P	0.025	≤ 0.025
S	0.010	≤ 0.010
Cr	17.582	17-19
Mo	2.697	2.25-3
Ni	14.086	13-15
Cu	0.080	≤ 0.50
Fe	Balance	Balance

3.2. Fatigue Testing

The eight-hole LCP which is used as a surgical implant in tibia fractures is shown in "Fig. 2". The specimen's length, width and thickness are 180 mm, 12 mm and 4 mm, respectively. Different locking systems may be chosen for surgery according to the type and position of fracture. A schematic of Tibia fracture and eight-hole LCP is shown in "Fig. 3" and the fracture is considered between hole 4 and 5.

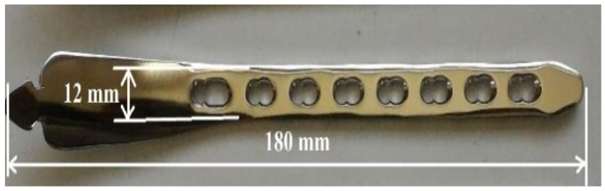

Fig. 2 Test specimen and its dimensions.

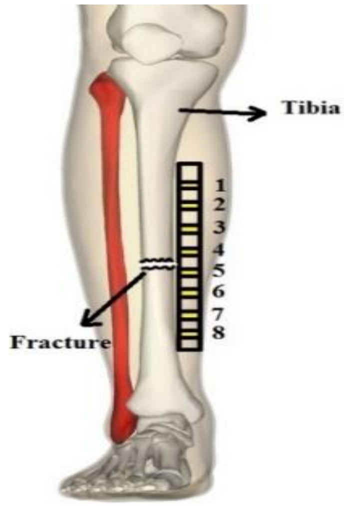

Fig. 3 Schematic of eight-hole LCP and tibial fracture.

Fatigue loading (R=0.1, 5 Hz frequency) was performed by installing a standard jig (ASTM F382-99 [20]) to Zwick/Roell Amsler HB100 testing machine ("Fig. 4") at 25 centigrade degrees' temperature and 60% relative humidity. The loading span is between the third and sixth hole. The applied load and displacement of loading noses were measured and submitted during the test. Six different load amplitudes were considered and fatigue tests were conducted for each of them. Post-failure experimentation was also conducted by scanning electron microscopy (SEM) in order to discuss failure mechanism at the fractured surface.

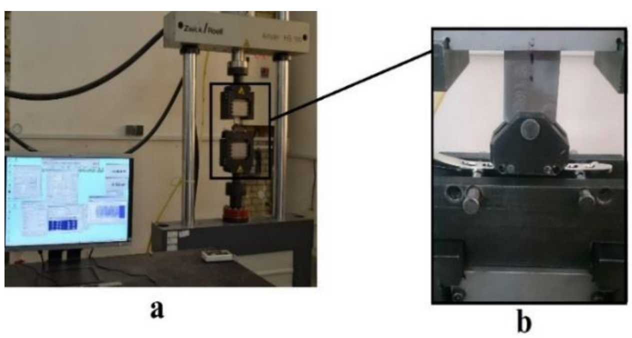

Fig. 4 The fatigue four-point bending test, (a): The Zwick/Roell Amsler HB100 testing machine and (b): The standard four-point bending jig.

4 RESULTS AND DISCUSSION

4.1. Fatigue Life Evaluation

Fatigue life cycles were evaluated for different maximum loads (500, 550, 600, 650, 700, 800, 900 and 1000 N). Each test was repeated for two times and the result of loads against the number of cycles is shown in "Fig. 5". It is assumed that it lasts two seconds for one load cycle in each leg [7], the patient walks 2 hours a day and it takes 9 months for the healing of fracture to tolerate the full load of walking. Besides that, if a patient with 100 kg weight is considered, 200% of his weight will be applied to each leg during gait. Thus, it can be assumed that a 2000 N force is applied to the upper part of LCP.

This force applies a 10 N.M bending moment to LCP holes because the head of LCP has 5mm misalignment to the holes. According to the distance between the loading nose and each support in four-point bending test, applying 500 N compression load leads to 15 N.M moment and consequently this force is selected for life estimation. For 500 N compression load, the fatigue life results were evaluated as 450000 cycles. According to the assumptions, this load cycle equals 125 days of walking. Therefore, it is advised that the patient should not apply full walking load up to 4th month after surgery.

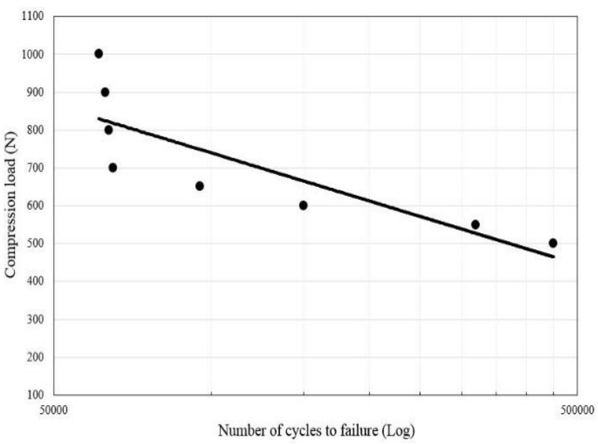

Fig. 5 Relation between compression load and fatigue life cycles.

4.2. Failure Mechanism

The fracture happened at loading span of four-point bending and the fatigue crack initiated from two sides of the locking hole ("Fig. 6"). As it is shown in "Fig. 7", fractured surface was observed by means of an optical microscope (OLYMPUS SZX9, Japan). The Crack was initiated from the side of the compression hole and beach marks illustrate the direction of crack propagation.

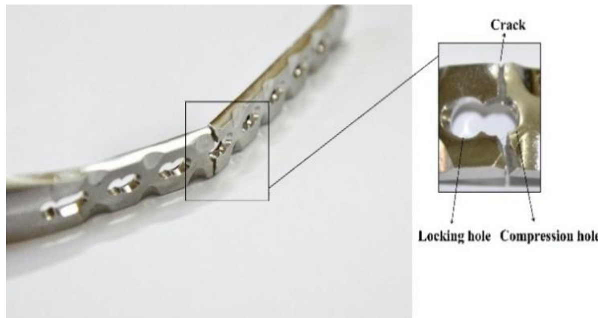

Fig. 6 Location of the fatigue crack at two sides of the compression hole.

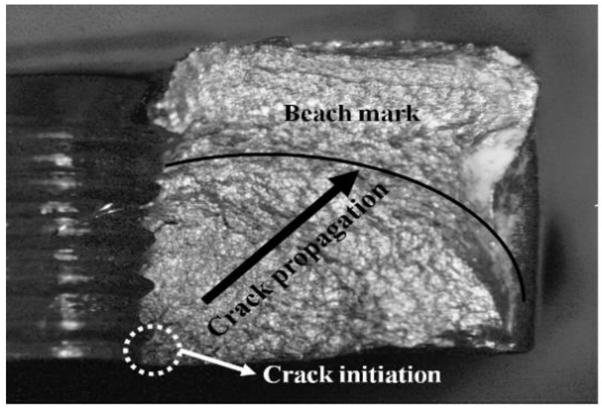

Fig. 7 The fracture surface of the compression hole by means of the optical microscope.

SEM observations revealed the striations on the fractured surface. "Fig. 8" shows the fatigue striations at 2 mm distance from the crack initiation site.

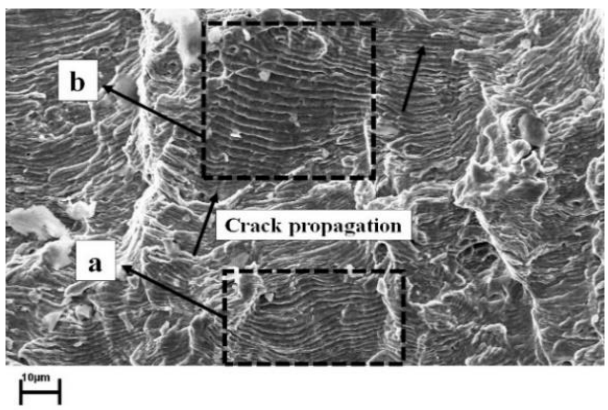

Fig. 8 Fatigue striations near the crack initiation site, (a): shorter striation spacing and (b): longer striation spacing.

It can be seen that the striation spacing near the crack initiation site is smaller than striation spacing far from the initiation site. Thus, the difference in length of striation spacing between these two points reveals the direction of crack propagation. "Fig. 9" shows the fatigue striation spacing at the middle of the fracture surface.

Four striation spacings were observed in the 10 µm scale of the SEM photo. Therefore, it can be concluded that there is a 2.5 µm distance between two striation spacing. If it is assumed that each striation spacing represents for one load cycle [21], the crack propagation life is estimated as 1600 cycles according to 4 mm thickness of LCP.

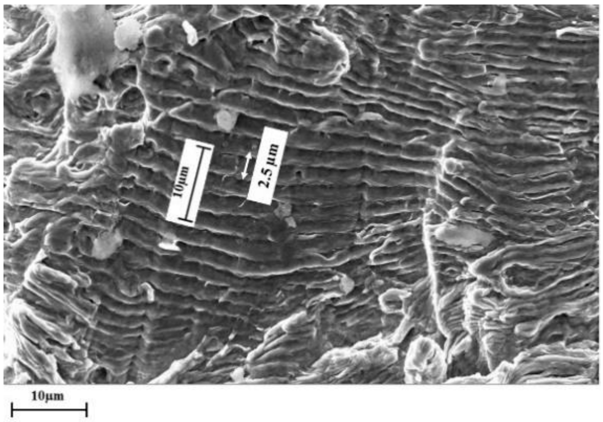

Fig. 9 Fatigue striation spacing at the middle of the fracture surface.

5 CONCLUSIONS

In this research, the fatigue life of the tibia locking compression plate (LCP) was evaluated under cyclic flexural loading and a post-failure investigation was carried out on the fracture surface. The following conclusions can be inferred from the results:

1- Fatigue life cycles were evaluated according to different compression loads during the four-point testing method. Consequently, the relation between compression load and life cycles was achieved and 450000 cycles were observed for 500 N compression load. According to the assumptions, this load cycle equal 125 days of walking. Therefore, it is advised that the patient should not apply full walking load up to 4th month after surgery.

2- Observations during the test and post-failure observations revealed that crack initiated from the edge of the compression hole and propagated from the lower to the upper surface. The results of optical microscope showed the crack growth direction according to the beach mark sizes.

3- Striations were observed on the fracture surface as a proof of fatigue crack growth. The striation spacing near the crack initiation site was smaller than striation spacing far from the initiation site. According to the scale of SEM result and the number of striation spacing in a unit scale, the number of cycles for fatigue propagation was estimated as 1600 cycles.

ACKNOWLEDGMENTS

This research was supported by Pars Orthopaedic Company, Mashhad, Iran. The authors would like to thank Pars Orthopaedic Company for supporting orthopaedic locking compression plates.

REFERENCES

[1] ASTM E1086 Standard, Standard Test Method for Analysis of Austenitic Stainless Steel by Spark Atomic Emission Spectrometry, American Society for Testing and Materials, West Conshohocken, 2014.

[2] ASTM F382-99 Standard, Standard Specification and Test Method for Metallic Bone Plates, American Society for Testing and Materials, Annual Book of ASTM Standards 13.01, 2003.

[3] ASTM F621-02 Standard, Standard Specification for Stainless Steel Forgings for Surgical Implants, American Society for Testing and Materials, In Annual Book of ASTM Standard, 2002.

[4] ASTM F138-03 Standard, Standard Specification for Wrought 18Chromium-14Nickel-2.5Molybdenum Stainless Steel Bar and Wire for Surgical Implants, American Society for Testing and Materials, in Annual Book of ASTM Standards, 2005.

[5] Gervais, B., Vadeana, A., Raisona, M., and Brochua, M., Failure Analysis of a 316L Stainless Steel Femoral Orthopedic Implant, Case Studies in Engineering Failure Analysis, Vol. 5-6, 2015, pp. 30-38.

[6] Izaham, R. M. A. R., Abdul Kadir, M. R., Abdul, Rashid, A. H., Golam Hossain, M. D., and Kamarul, T., Finite Element Analysis of Puddu and Tomofix Plate Fixation for Open Wedge High Tibial Osteotomy, Injury, Vol. 43, No. 6, 2012, pp. 898-902.

[7] Kanchanomai, C., Phiphobmongkol, V., and Muanjan, P., Fatigue Failure of an Orthopedic Implant- A Locking Compression Plate, Engineering Failure Analysis, Vol. 15, No. 5, 2008, pp. 521-530.

[8] Kim, S., Chang, S., and Jun, H., The Finite Element Analysis of a Fractured Tibia Applied by Composite Bone Plates Considering Contact Conditions and Time Varying Properties of Curing Tissues, Composite Structures, Vol. 92, No. 9, 2010, pp. 2109-2118.

[9] Marcomini, J. B., Baptista, C. A. R. P., Pascon, J. P., Teixeira, R. L., and Reis, F. P., Investigation of a Fatigue Failure in a Stainless Steel Femoral Plate, Journal of Mechanical Behavior of Biomedical Materials, Vol. 38, 2014, pp. 52-58

[10] Nassiri M., MacDonald, B., and O'Byrne, J. M., Computational Modeling of Long Bone Fractures Fixed with Locking Plates- How Can the Risk of Implant Failure Be Reduced?, Journal of Orthopaedics, Vol. 10, No. 1, 2013, pp. 9-37.

[11] Okazaki, Y., Comparison of Fatigue Properties and Fatigue Crack Growth Rates of Various Implantable Metals, Materials, Vol. 5, No. 12, 2012, pp. 2981-3005.

[12] Sepehri, B., Ashofteh Yazdi, A. R., Rouhi, G. A., and Kashani, M. B., Analysis of the Effect of Mechanical Properties on Stress Induced in Tibia, Proceedings of 5th Kuala Lumpur International Conference on Biomedical Engineering, Springer, Berlin, Heidelberg, 2011, pp. 130-133.

[13] Sepehri, B., Rameshi, M., Effect of Placement and Material Properties of Tibial Plate on Stress Pattern at Fractured Site. Modares Mechanical Engineering, Vol. 14, No. 11, 2014, pp. 151-165 (In Persian).

[14] Sepehri, B., Taheri, E. and Ganji, R., Biomechanical Analysis of Diversified Screw Arrangement on 11 Holes Locking Compression Plate Considering Time-Varying Properties of Callus, Biocybernetics Biomedical Engineering, Vol. 34, No. 4, 2014, pp. 220-229.

[15] Shaat M., Reporting the Fatigue Life of 316L Stainless Steel Locking Compression Plate Implants: The Role of Femoral and Tibial Biomechanics During the Gait, Journal of Biomedical Engineering, Vol. 139, No. 10, 2017, pp. 1-5

[16] Snow, M., Thompson, G., and Turner, P. G., A Mechanical Comparison of the Locking Compression Plate (LCP) and the Low Contact Dynamic Compression Plate (DCP) in an Osteoporotic Bone Model, Journal of Orthopaedic Traumatology, Vol. 22, No. 2, 2008, pp. 121-125.

[17] Tsai, S., Fitzpatrick, D. C., Madey, S. M., and Bottlang, M., Dynamic Locking Plates Provide Symmetric Axial Dynamization to Simulate Fracture Healing, Journal of Orthopaedic Research, Vol. 38, No. 8, 2015, pp. 1218-1225

[18] Uhthoff, H. K., Poitras, P., and Backman, D. S., Internal Plate Fixation of Fractures: Short History and Recent Developments, Journal of Orthopaedic Science, Vol. 11, No. 2, 2006, pp. 118-126.

[19] Zamani, P., Jaamialahmadi, A., and Shariati, M., Ductile Failure and Safety Optimization of Gas Pipeline, Journal of Solid Mechanics, Vol. 8, No. 4, 2016, pp. 744-755.

[20] Zhang, J., Ebraheim, N., Li, M., He, X., Schwind, J., Liu, J., and Zhu, L., External Fixation Using Locking Plate in Distal Tibial Fracture: A Finite Element Analysis, European Journal of Orthopaedic Surgery Trauma, Vol. 25, No. 6, 2015, pp. 1099-1104.