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MONITORING TECHNIQUES OF BONE FRACTURE HEALING USING EXTERNAL FIXATORS

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Long bone fractures can be healed using external fixators – devices that stiffly fix the fractured fragments, attached to the bone by pins parallel to the bone frame. This method enables to benefit both from healing and diagnostics of fracture during osteogenesis. Osteogenesis, traditionally diagnosed using X-rays methods (RTG, densitometry), can also be more precisely determined with mechanical properties like strength and stiffness inside the fracture slot. The treatment of long bone fractures by external fixators offers a unique opportunity to control the healing of the fracture by measuring the compression forces on the frame, that occurs under the load applied to the bone and depends on the mechanical properties of the fracture. The procedure of measurement of the compression force on the frame can be performed using tensometers, what is a cheap and simple method, and can be performed by the patient at home. The measurement of osteogenesis gives a possibility of more precise diagnostics of the fracture. It can also be combined with computer techniques like artificial intelligence. The paper presents one of the methods of monitoring the bone fracture healing.

Key words: External fixators, fracture healing, osteosynthesis, bone strength and stiffness

1. Introduction

Frequent injuries, bone fracture, an effect of loads much larger than the bone can carry, can be healed by using external fixators. Fracture fragments should be relatively stiffly fixed together to provide best healing conditions [5, 6]. To fix both parts of the broken bone, the external fixator provides a stiff frame, parallel to the bone, rigidly attached to the bone by pins (see Fig. 1).

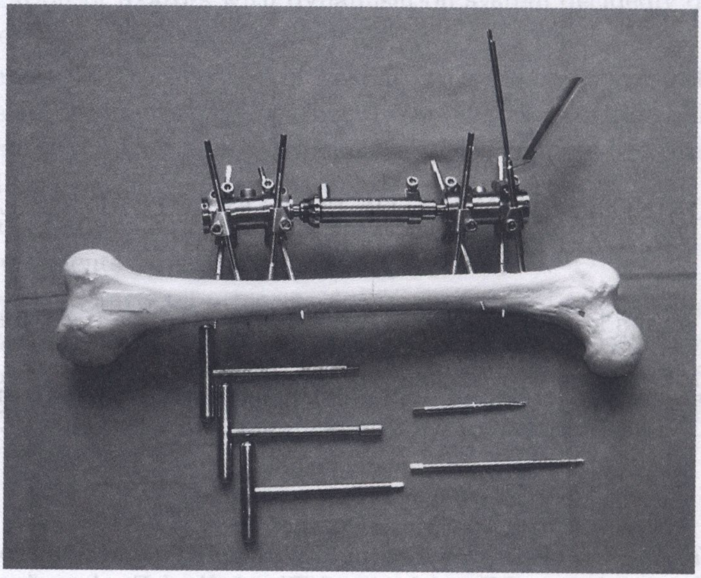

FIG. 1. Fixator Dynastab Mechatronika 2000 (to long bones) with instrumentation.

This method of fracture healing gives a unique opportunity to benefit from both healing and diagnostics during the osteogenesis (bone growth process).

Clinical and experimental observations have demonstrated that the fracture healing process (osteogenesis) changes broken bone condition in a particular physiological way. Bone healing is associated with relative paucity of callus and osteonal remodelling across the fracture line. The non-invasive evaluation of fracture healing may allow more precise timing of fixation device removal, recommendation for progression from non-weight bearing to full weight bearing, and to the prediction of abnormal fracture healing such as delayed union or non-union. The common techniques include manual examination of the fracture for stability, radiographic evidence of healing, and the empirical passage of time. Traditional diagnostics methods: X-ray techniques such as radiography, radiographic densitometry, Computed Tomography provide the information concerned with mineral properties of the healed fracture and fracture site, and can describe the fracture healing as a process of calcification. This may be not sufficient to evaluate the real fracture condition and may cause a risk of non-union or refracture. Many fractures can bear load before their "empirical healing time" and are therefore immobilised for an unnecessarily long period. Others are freed too soon and may sustain refracture or develop malunion after early activity. A fracture that is sufficiently healed to allow normal activities may not have sufficient strength for strenuous work or vigorous sport.

The treatment of the fracture using external fixators enables one to diagnose the healing process by measuring the mechanical properties inside the fracture slot. Direct measurement of mechanical properties of the healed bone treated by external fixators gives precise information about the fracture conditions. The proposed method provides an opportunity to find a bone-healing pattern based on mechanical properties of the fracture and to propose a measure of healing the fracture, which would define the stadium of the healing process. The measurement of the strain in the fixator frame by strain gauges was developed by BURNY *et al.* [3] and was subsequently improved in the next years.

2. MATERIALS AND METHODS

The direct technique for the measurement of stiffness proposed by RICHARDSON (1988) involves a temporary removal of the fixators frame [3]. The method of the fracture stiffness measurement is shown in Fig. 2.

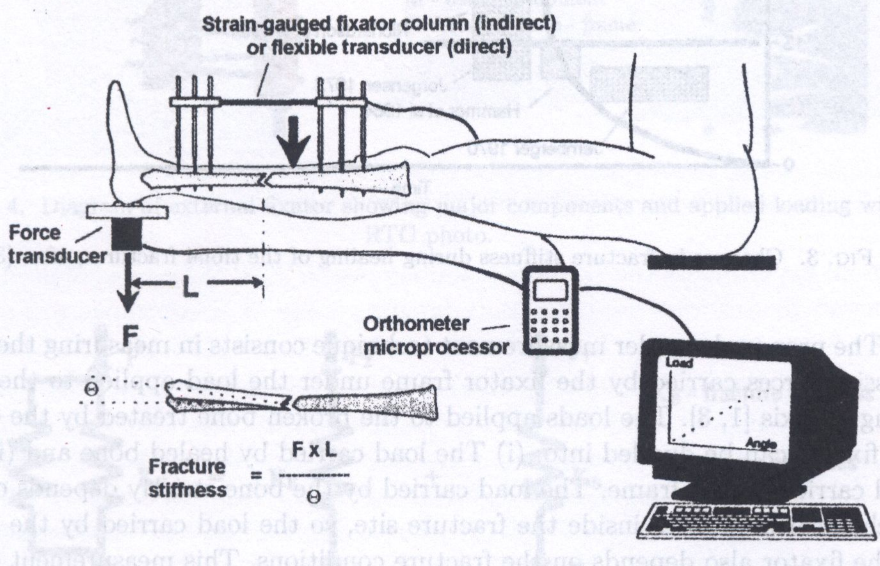

FIG. 2. Direct method of fracture stiffness measurement, after [3].

According to in this method, the fracture stiffness is defined by the relation:

$$\text{Fracture stiffness} = \frac{F \cdot L}{\theta},$$

where F is the applied force, L is the distance from fracture slot to the heel and θ is the measured angle. The results of the fracture stiffness measurement are shown in Fig. 3 as their characteristics in time.

The measurement procedure is more complex when the fixators frame is not prepared to be removed and was used only after six weeks after injury, when the clinical examination was also appropriate. The bending moment, which was measured on the flexible strain gauge, may cause many inaccuracies when different types of fractures are examined.

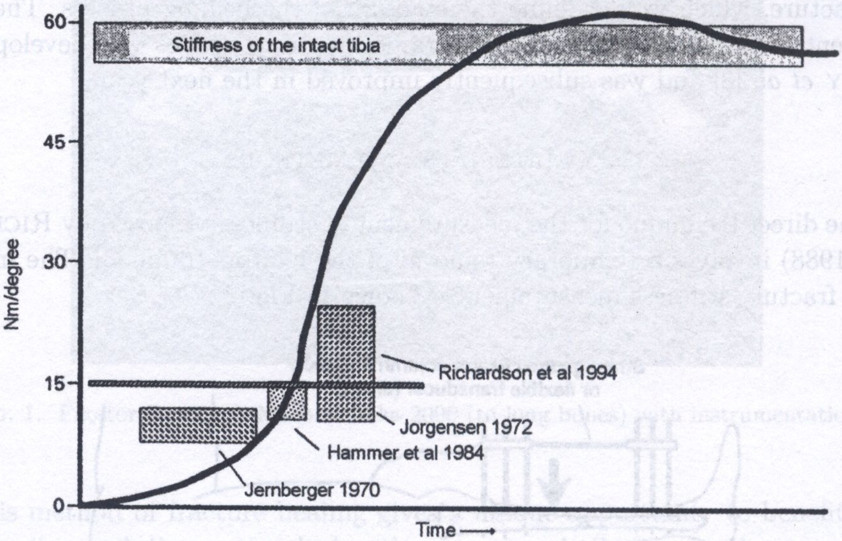

FIG. 3. Changes in fracture stiffness during healing of the tibial fractures, after [3].

The proposed simpler measurement technique consists in measuring the compressive forces carried by the fixator frame under the load applied to the bone along its axis [1, 3]. The loads applied to the broken bone treated by the external fixator can be divided into: (i) The load carried by healed bone and (ii) the load carried by the frame. The load carried by the bone strictly depends on the mechanical properties inside the fracture site, so the load carried by the frame of the fixator also depends on the fracture conditions. This measurement of the reduced stress in the fixator frame is an indirect assessment and does not provide an objective measurement of stiffness in absolute units, but can be successfully used as a definition of bone healing.

The external fixation system is schematically shown in Fig. 4, excluding the biological contributions to the stiffness of the fracture from the soft tissues and the surrounding muscles. These small contributions are considered to be negligible in theoretical mechanical analysis. It is also assumed that there is a rigid bond between the screws and the bone as well as between the screws and the frame of the fixator.

Idealised model of bone-fixator system (Fig. 5) consists of a load F_1 carried by healed bone, and load F_2 carried by fixator's frame, which give the total load applied to the system F:

$$F = F_2 + F_1. \tag{2.1}$$

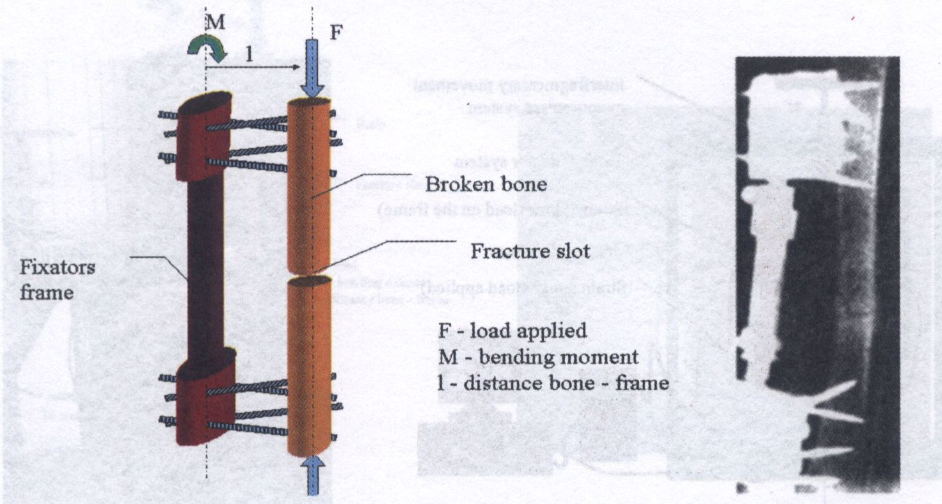

FIG. 4. Diagram of external fixator showing major components and applied loading with RTG photo.

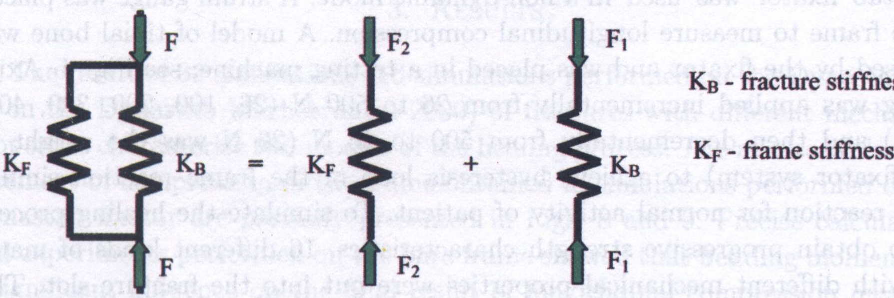

FIG. 5. Diagram of idealised fixator system as a two-spring system.

The load can be defined as a sum of axial compression and bending moment. The bending moment depends strictly on the length of bone screws, on bone shape and bone/fixator system configuration, which is different for each patient. The main point of the measurement technique is to exclude the influence of bending moment on the measured value of compression, and make the fracture healing measure independent of the kind of fracture. Then the fracture healing measurement value can be determined as:

$$m = \frac{F_2}{F} = \frac{F_2}{F_1 + F_2} \tag{2.2}$$

and it should tend, to be zero when the fracture is successfully healed [8, 9, 10].

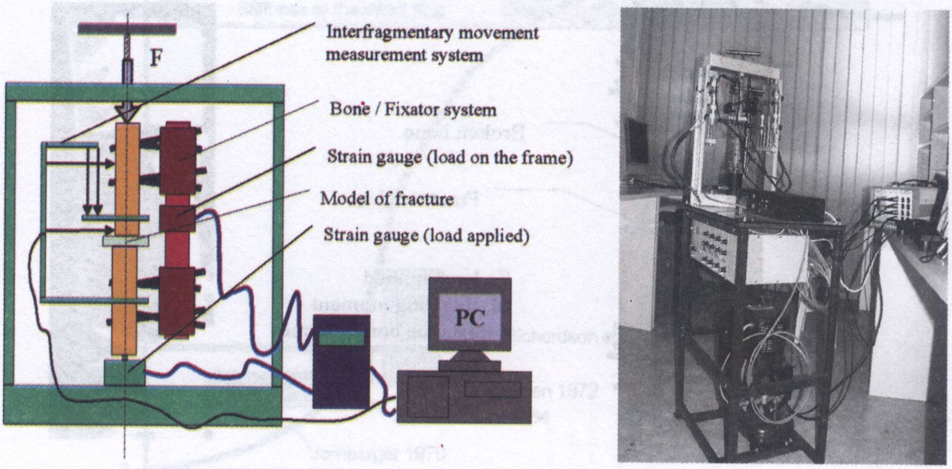

FIG. 6. Diagram of test equipment and testing machine.

In all experiments the Dynastab and Dynastab 2000 fixators were used. The Dynastab fixator was used in a non-dynamic mode. A strain gauge was placed on the frame to measure longitudinal compression. A model of tibial bone was stabilised by the fixator and was placed in a testing machine, see Fig. 4. Axial loading was applied incrementally from 26 to 500 N (26, 100, 200, 300, 400, 500 N) and then decrementally from 500 to 26 N (26 N was the weight of bone/fixator system) to achieve hysteresis loop of the frame reaction similar to the reaction for normal activity of patient. To simulate the healing process and to obtain progressive strength characteristics, 16 different kinds of materials with different mechanical properties were put into the fracture slot. The total load, the longitudinal compression forces on the frame, and the interfragmentary movements were measured. The total load and compression force on the frame were measured using strain gauge systems scaled in N with accuracy to 1 N. Interfragmentary movements were measured using 4 electromagnetic length-measuring probes characterised in mm, with accuracy of 0.001 mm. The same examination procedure was applied to the Dynastab Mechatronika 2000 fixator used in a dynamic mode. A separate strain gauge was attached to the frame to measure the longitudinal compression. The fixator was used to stabilise a model of the hip bone, and was also placed in a testing machine to load. We observe that in this case the axis of the applied load did not coincide with the bone axis. The diagrammatic form of the Dynastab Mechatronika 2000 fixator is shown in Fig. 7.

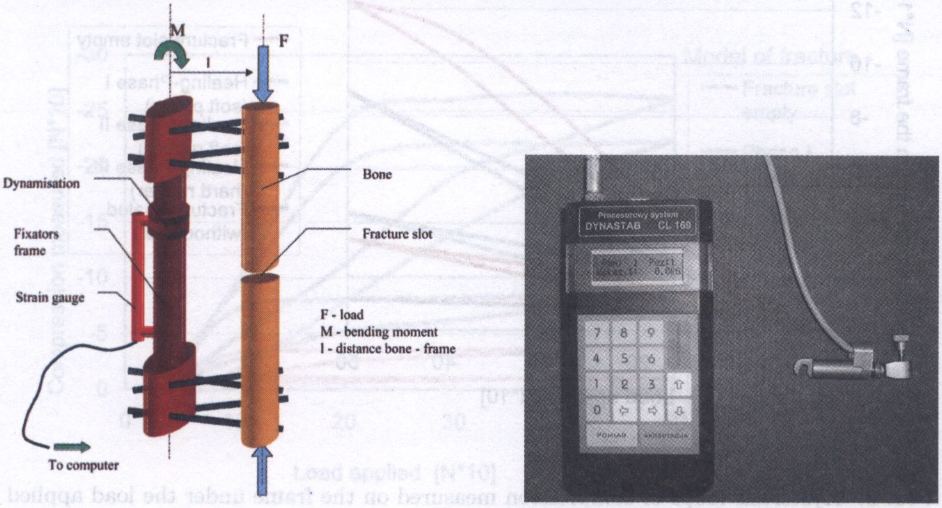

FIG. 7. Diagram of Dynastab Mechatronika 2000 external fixator showing major components and applied loading with photo of the disconnectable strain gauge.

3. Results

The result of 32 simulations (16 simulations performed on the Dynastab and 16 on the Dynastab Mechatronika 2000) of fractures with different mechanical properties characterise two models of the healing process. The results of the measurement of compression in the frame obtained in simulations performed on the Dynastab fixator are partially presented in Figs. 8 and 9. Precise calculations and experiments performed on the bare frame showed that bending moment had a significant influence on the final result of longitudinal compression measurement, and was added to it. The bending moment did not cause any inaccuracy, because the dimensions and the configuration of the bone-fixator system were kept unchanged.

Furthermore we note that the presented graphs (Figs. 9 and 11) of the model of the healing process are not a function of time!

The analysis of the results shows that the greater the load and the more advanced is the stadium of the fracture healing, the more precise measurements of fracture healing can be obtained. The greater is the load, the greater measured compression on the frame and the smaller will be the inaccuracy. If the more advanced stadium of the fracture healing is examined, then the hysteresis loop is narrower.

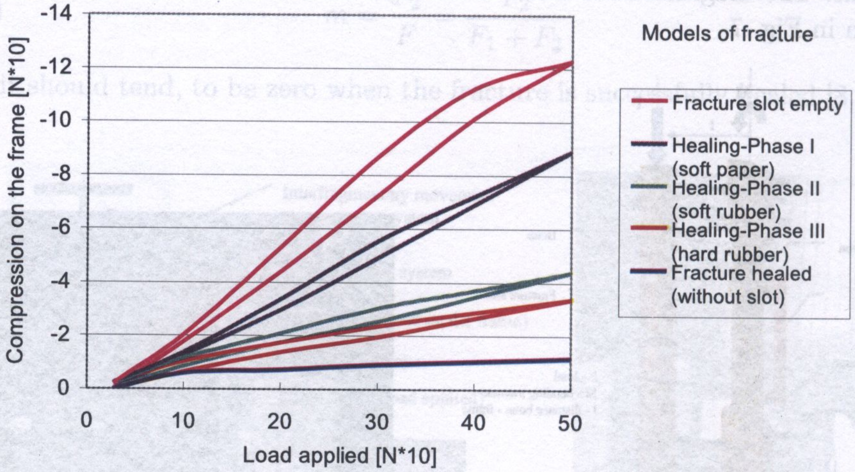

FIG. 8. Hysteresis loops of compression measured on the frame under the load applied for 5 models of fracture strength.

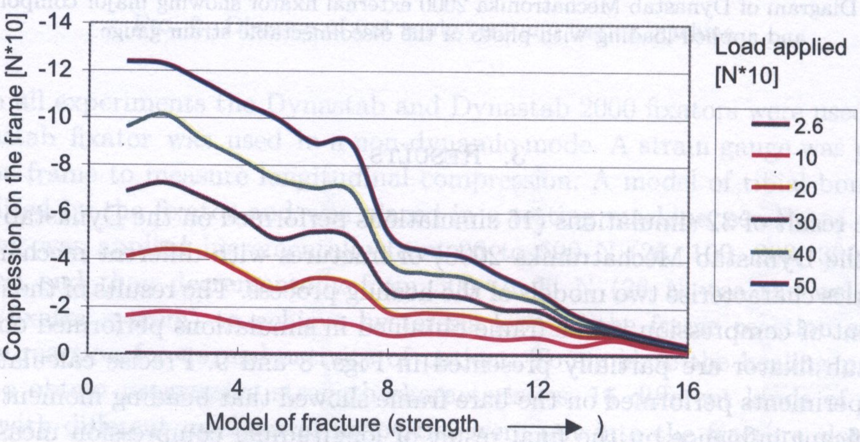

FIG. 9. A model of healing process pattern obtained under different loads applied to the bone.

The results of the measurement of compression on the frame obtained in simulations performed on the Dynastab Mechatronika 2000 fixator are partially presented in Figs. 10, 11. The fixator frame and separate strain gauge were designed to exclude the bending moment during the measurement, so only the compression on the frame was measured. The significant hysteresis loops that appeared in the experiments are caused by the lack of resiliency in the dynamisation module of the fixators frame and by low resiliency in the fracture slot that did not provide sufficient force to recoil the dynamisation.

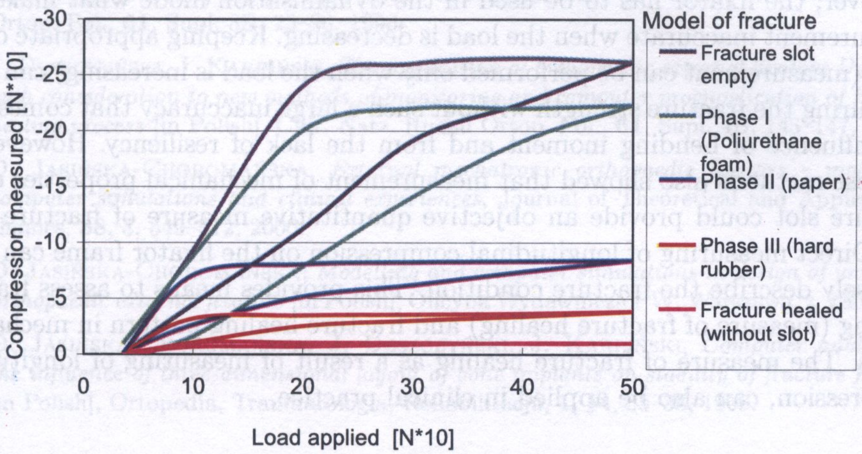

FIG. 10. Hysteresis loops of compression measured on the frame under the load applied for 5 models of fracture strength.

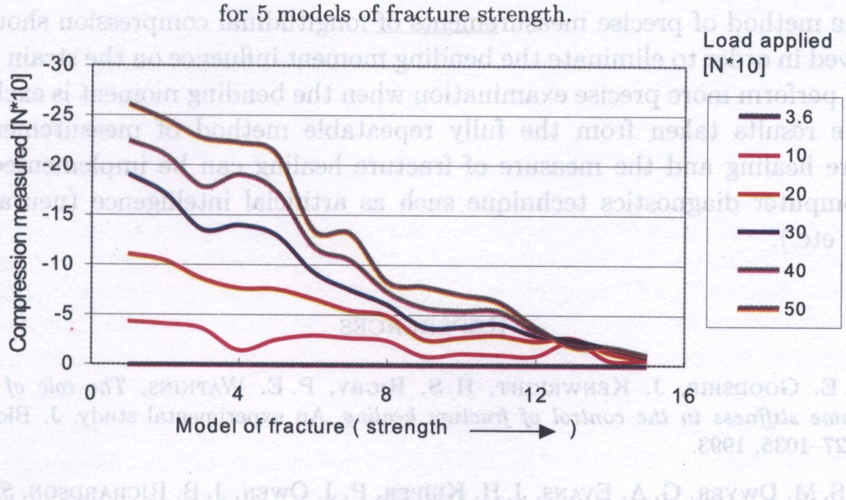

FIG. 11. A model of healing process pattern obtained under different loads applied to the bone.

4. DISCUSSION

The noninvasive evaluation of fracture healing may allow more precise timing of fixation device removal, quantitative recommendations for weight bearing, and the prediction of abnormal fracture healing patterns.

The influence of bending moment makes the presented method of longitudinal compression measurement not repeatable for different kinds of bones and for different types of fractures, so they are not comparable between individual patients. The separation of the strain gauge from the frame of the fixator having the measurement excludes the influence of the bending moment (third method). However, the fixator has to be used in the dynamisation mode what makes the measurement inaccurate when the load is decreasing. Keeping appropriate conditions (measurement can be performed only when the load is increasing) can allow measuring the fracture strength without such a large inaccuracy that comes from the influence of bending moment and from the lack of resiliency. However, all of these methods also showed that measurement of mechanical properties of the fracture slot could provide an objective quantitative measure of fracture healing. Direct measuring of longitudinal compression on the fixator frame can more precisely describe the fracture condition. This provides means to assess fracture healing (measure of fracture healing) and fracture healing pattern in mechanical terms. The measure of fracture healing as a result of measuring of longitudinal compression, can also be applied in clinical practice.

5. Conclusions

The method of precise measurements of longitudinal compression should be improved in order to eliminate the bending moment influence on the strain gauge and to perform more precise examination when the bending moment is excluded.

The results taken from the fully repeatable method of measurements of fracture healing and the measure of fracture healing can be implemented into the computer diagnostics technique such as artificial intelligence (neural networks, etc.).

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