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Various Applications of the Digital Image Correlation Method in the Experimental Analysis of Biomechanical Problems

G. Cabaj [1,a], P. Boháč [1], T. Návrat [1], P. Vosynek [1], V. Apostolopoulos [2], L. Kunz [3], J. Beneš [4]

[1] *Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896, 616 69 Brno, Czech Republic*
[2] *First Department of Orthopaedic Surgery, St. Anne's University Hospital and Faculty of Medicine, Masaryk University, Brno, Czech Republic*
[3] *Institute of Physics of Materials, Czech Academy of Sciences, Brno, Czech Republic*
[4] *BT Medical Engineering, Inc, Rozsochy, Czech Republic*
[a] *gabriel.cabaj@vutbr.cz*

Abstract: Nowadays, optical strain measurement using the digital image correlation (DIC) method is a frequently used experimental analysis method in various engineering fields. The main advantage is that it is a non-invasive method, therefore it is possible to analyze areas on structures that could be inaccessible to conventional contact methods. This paper aims to present various applications of the use of the digital image correlation method in biomechanical applications and specific case studies are presented using a commercial software Alpha from X-Sight company.

Keywords: biomechanics; strain analysis; digital image correlation; optical measurement; experimental modelling.

1 Introduction

Several experimental analyses using the DIC in the field of biomechanics are presented in this paper. It presents the possibilities of optical strain analysis, which compared to traditional contact methods, offers wider possibilities for experimental analysis of components. Examples are given where it is necessary to analyze the displacements of individual points on a component but also to analyze the whole region and evaluate the field of the strains.

In this paper, optical deformation analyses using a commercial DIC system and X-Sight's Alpha software are presented. Depending on the type of problem to be solved, the capabilities of this software are used to evaluate the displacements or strains on the analyzed object. The purpose is to show the capability of the optical method, which comes where traditional contact methods of measuring deformations are not sufficient.

The experiments presented involve the determination of the strain distribution on an orthopaedic orthosis during a cyclic test. Later, the analysis of the composite pelvic bone model before and after the application of the fixator is described. The last two sections are dedicated to the analysis of the fixed fracture of the humerus and the compression test of implanted total knee endoprostheses in the composite tibial bone.

2 Method

The DIC method is a popular tool used today for non-contact deformation measurement. Its basic principle involves tracking the displacement of a surface by analyzing successive digital images captured during the loading of a specimen. The reference digital image of the undeformed specimen is compared with the following image of the deformed specimen so that the strains can be evaluated based on the computed displacements. Each tracked point in the image is represented by a unique set of pixels from its surroundings (subset). Due to this uniqueness, it is then possible to use digital correlation to determine the new position of this subset of pixels in the next frame and thus quantify the displacement of the point represented by this subset of pixels [1].

This method can be used either to measure displacements in the plane using a single camera or to measure displacements in 3D space using at least two cameras. If two cameras are used, the measurement in 3D space is performed by capturing the image from different views at stereo camera angles. Using triangulation, it is then possible to calculate the position of a point in space and subsequently its displacement [1].

3 Strain Analysis of 3D Printed Orthopedic Orthoses

3.1 Problem Description

Supramalleolar orthosis is a type of orthotic device that is primarily used to stabilize the ankle and foot of patients. These orthoses are designed to provide control over the ankle joint but still allow for natural movement and sufficient flexibility. An example of such a device is shown in Fig. 1. It is 3D printing technology that is the appropriate way to produce such devices. Thanks to its high flexibility, this method can be used to create personalized orthoses directly tailored to patients. In addition to the fact that 3D printing enables rapid prototyping, 3D printed materials also can exhibit much better mechanical properties than conventional materials. This significantly increases the durability and reliability of these orthoses [2–4].

Fig. 1: Analyzed object – supra malleolar orthosis for ankle support primarily designed for young patients with pronation and low tone [5].

The main objective of this work was the experimental comparative analysis of the mechanical response of the ankle orthosis to the loads to which it is subjected during the period of use by the patient. The ankle orthosis is primarily cyclically loaded daily, while the patient walks. However, significant loading occurs mainly when the orthosis is placed on the patient's foot. In this case, there must be a significant deformation of the orthosis for it to be placed on the foot [6]. The analysis of the strain field under quasi-static loading is primarily used to identify potential critical areas and can be used for component optimization. In this work, in addition to quasi-static loading, the response of the component to cyclic loading is also investigated.

3.2 Experiment Description

In this work, a 3D measurement with two cameras was used. The cameras had 9 MPx resolution and 67 Hz frame rate. The resolution of the given camera configuration was 0.3 µm. Before the actual measurement, it was necessary to calibrate the 3D DIC system. The component was placed at 268 mm in from of both cameras, with the lateral direction perpendicular to the image.

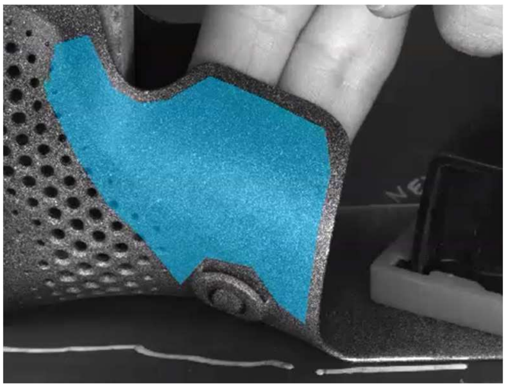

Fig. 2: Analyzed orthosis with shown area of interest.

Since the orthosis is mostly stressed when placed on the patient's foot, several orthoses with different designs were subjected to this stress, and their response was evaluated. The loading method was chosen with consideration of the orthosis loading in reality. Therefore, the orthosis was loaded as it would be when placed on the foot. Specifically, by pushing off the side of the orthosis with the patient's hand. Component loading was controlled by finger displacements in the lateral direction. As the value of the displacements was evaluated by the DIC system during the test, it was ensured that the same displacement in the lateral direction was provided for each version of the component. The loading was quasi-static.

Each component was subjected to two load cases. In the first case, it was only one load cycle with a maximum lateral displacement of 8 mm. In the second load case, the maximum lateral displacement on the component was 23 mm and 50 load cycles were performed.

3.3 Obtained Results

Overall, several different sizes of ankle orthoses were analyzed. For simplicity, only two (the biggest and the smallest) of them are presented in the comparative analysis. Since a comparative analysis was performed, the results of the field strains (first principal strain) are always presented with a consistent legend in each figure.

Comparing Figs 3 and 4, it can be concluded that the character of the strain distribution is very similar. The extreme values are localized around the rounded part – the notch. As this is a commercial product, the specific value of the results is not disclosed. The results of the analysis were used by the orthosis manufacturer to further optimize the products.

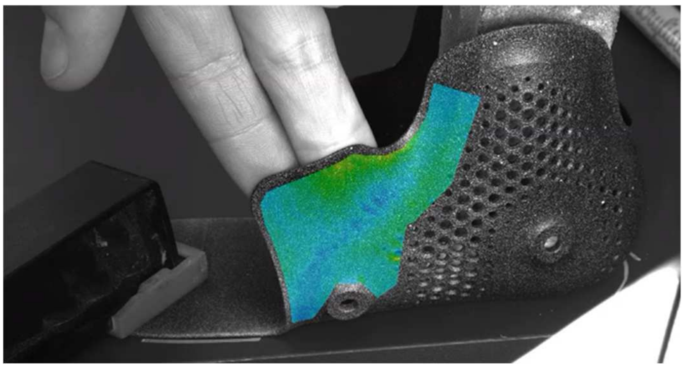

Fig. 3: First principal strain distribution on bigger ankle orthosis during static loading.

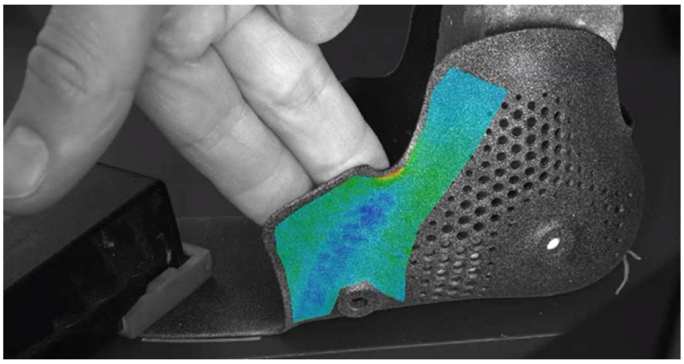

Fig. 4: First principal strain distribution on a smaller version of ankle orthosis during static loading.

Another interesting was the response of the orthoses to cyclic loading. Under full load, the character of the deformation was like that of the quasi-static loading method – see Fig. 5. After unloading under cyclic loading, clear areas of plastic strain are visible. These areas may be critical concerning fatigue, the areas are visible in Fig. 6.

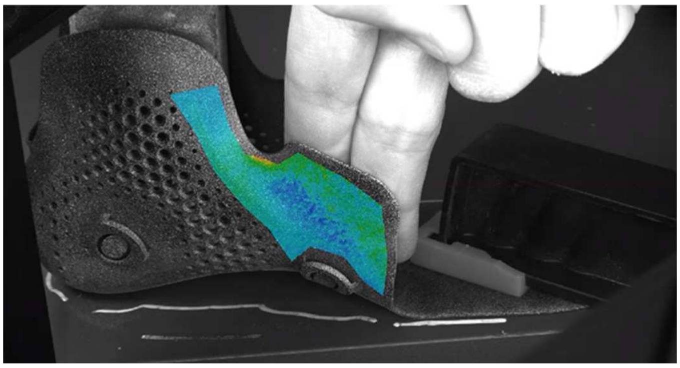

Fig. 5: First principal strain distribution on a bigger version of ankle orthosis during cyclic loading.

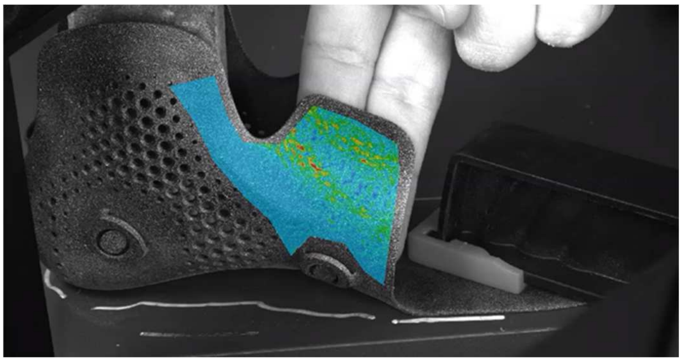

Fig. 6: Residual strain region on bigger version of ankle orthosis after cyclic loading.

4 Analysis of Strain and Displacement on a Composite Model of the Pelvic Bone

4.1 Problem Description

When the pelvic bone is injured and damaged, especially in the area of the symphysis, in common practice, it is then surgically fixed by the addition of a fixator.

The problem that was analyzed in this case can be divided into two parts. In the first case, the effect of the addition of the fixator on the distribution of the stress in the pelvis compared to the undamaged pelvis was analyzed. This is particularly important from the point of view of the patient's recovery, to answer the question of whether a fixed pelvis would be more susceptible to damage outside the region of the fixator.

In the second case, an analysis of the stress on the fixator after its application is required. This is because of its optimal design with regard to the risk of damage, especially by fatigue fracture. What is also analyzed is the effect of fixation – the number of screws [7].

4.2 Experiment Description

The experiment was carried out on an electrodynamic INSTRON E10000 testing machine. The axis of the loading force was the hip joint and the junction of the pelvis with the sacrum – see the picture below.

The whole experiment consisted of several load conditions. The response to quasi-static loading of the pelvis, with different magnitudes of loading force, was analyzed. The magnitude of the force was chosen with the consideration that the patient in recovery may start loading the pelvis gradually after surgery. Thus, each of these loading levels was evaluated.

In the next phase, the force with a different amplitude from the quasi-static test was again applied, but the loading in this case was done cyclically with a frequency of 0.5 Hz and 1 Hz.

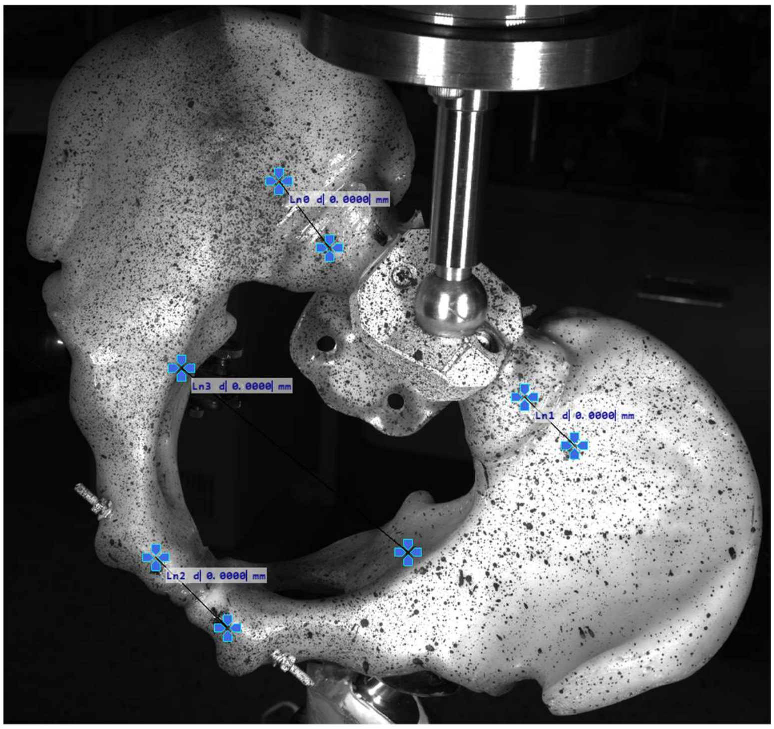

Fig. 7: Pelvic bone loading in a universal testing machine and identified measured positions.

4.3 Obtained Results

Based on the measured values of the change in individual lengths between the points shown in Fig. 7, the global behavior of the undamaged and fixed pelvic bone was analyzed.

In the next part of the experiment, the stress on the surface of the fixator (Fig. 8) was evaluated under static and cyclic loading. This was done by measuring the strains on the fixator using the DIC and converting these strains to the corresponding stresses based on the material's value of Young's modulus of elasticity. The obtained data are essential for the prediction of the fatigue life of the fixator for its design modifications.

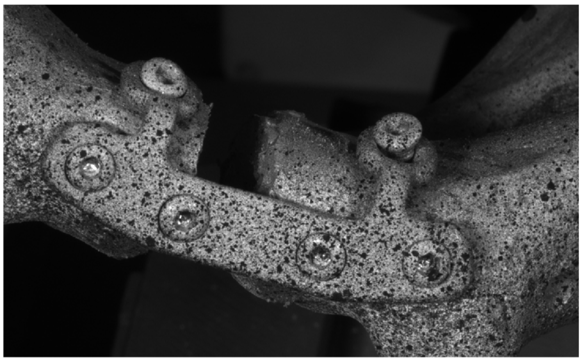

Fig. 8: Analyzed fixator – detailed view.

5 Analysis of Displacements after Fixation of Humerus Fracture

5.1 Problem Description

In a fracture of the humerus between the bone diaphysis and epiphysis, it is subsequently fixed with a fixator that is inserted into the axis of the bone. In this case, the aim was to determine how the humerus behaves with a fixed fracture. Specifically, whether there is significant relative motion between the humerus head and the diaphysis of the humerus. Subsequently, the influence of the type of fixation was also analyzed.

5.2 Experiment Description

The humerus was loaded with a certain force in a universal testing machine with the help of a special fixture that simulated the 90° abduction that occurs when raising the arm. Thus, 500 cycles were performed and the motion of the points shown in Fig. 9 was analyzed. In this case, DIC was only used to analyze the displacements of individual points from which the relative motion of the two parts, the humerus head and the diaphysis, could be determined.

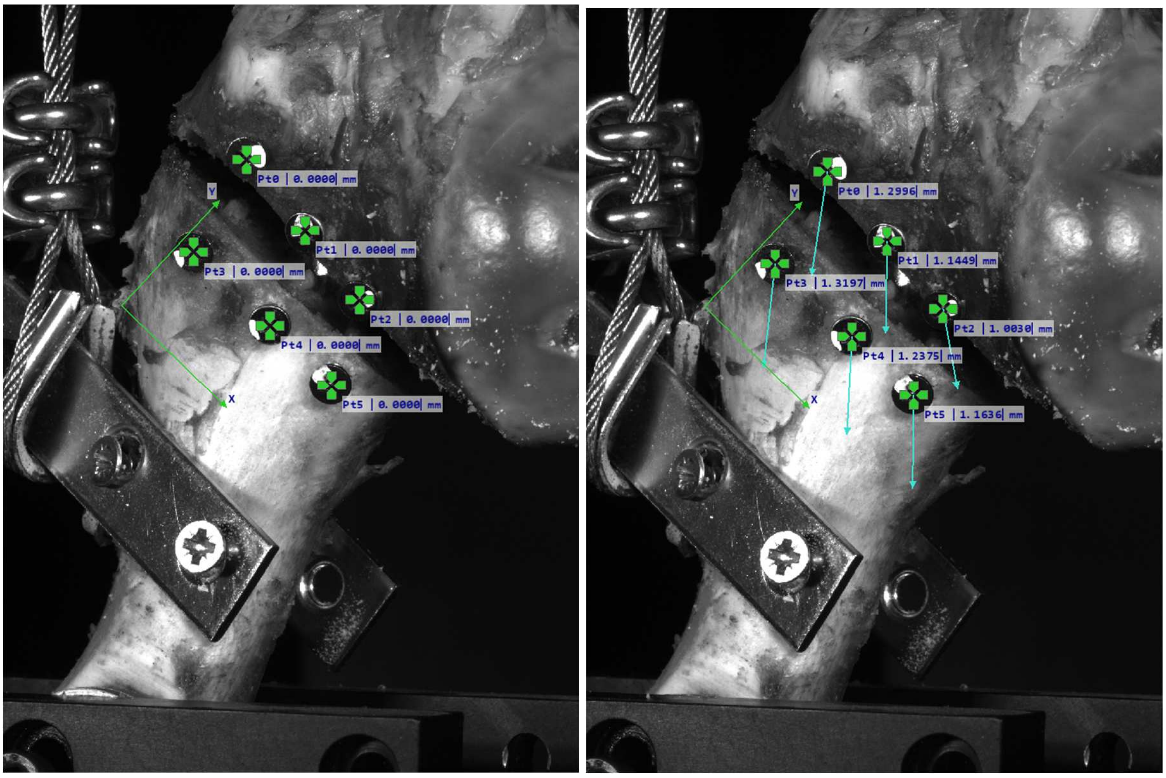

Fig. 9: Analysis of deformations in fixed humerus fracture. Relaxed state on the left and loaded state on the right. Displacements on the capitellum and the bone are shown.

5.3 Obtained Results

From the subsequent processing of the displacements of the individual points, it was possible to assess the relative movement of the two mentioned parts qualitatively and quantitatively. These results are important for the clinician in the choice of the implant and the method of its placement. Due to confidentiality, specific results are not reported.

6 Analysis of the Tibial Bone in the Compression Test

6.1 Problem Description

The final treatment of gonarthrosis involves the implantation of a total knee endoprosthesis that interacts with the tibial bone. The experimental analysis using DIC aimed to assess the effect of different types of implants on the mechanical response of the cortical bone tissue model to the composite tibial bone. This experiment was also part of a wider research with computational modelling using the finite element method [8–10].

6.2 Experiment Description

The tibia with implanted tibial part of total knee replacement was loaded using a femoral component in compression. Two different total knee prostheses were analyzed in this way. The setup of loading is presented in Fig. 10 [8–10].

Fig. 10: Compression test of the tibial bone with the applied total knee replacement [8].

6.3 Obtained Results

Using Alpha software, the field of strain on the surface of the cortical bone tissue in the proximal tibial bone area was evaluated. Together with computational modelling, these results can be used to assess the impact of different types of implants [8–10].

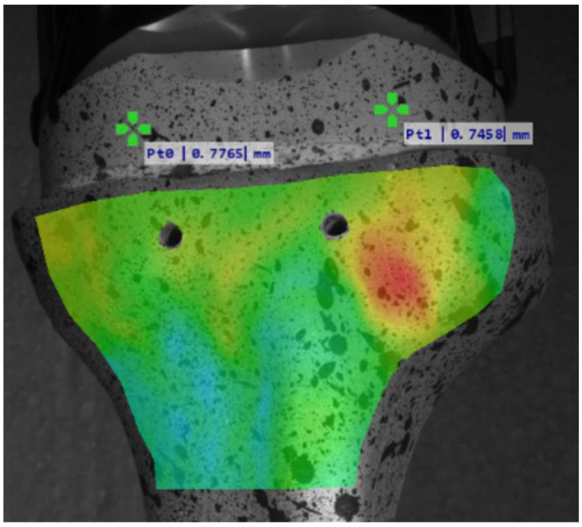

Fig. 9: Strain distribution on loaded tibial bone [8].

7 Conclusion

In this paper, several experimental analyses in the field of biomechanics using the digital image correlation method have been described.

Using the DIC system and Alpha software were used to analyze the mechanical response of the orthotic orthoses and provide the manufacturer with information that can be used in the further development of these orthoses.

In the optical analysis of displacements on the pelvic bone, the results can be used to assess the effect of the addition of a fixator on changing the character of the strain on the pelvic bone. Further, this analaysis enables us to determine the stress state on the fixator. This knowledge is crucial for the prediction of the fixator lifetime.

Analysis of the influence of the fixator was also performed in the case of humerus fracture. Here, the relative movement between the humerus head and the diaphysis after implant placement was analyzed.

The last case study presents an analysis of the strain distribution on the surface of the cortical tissue of the tibial bone during the application of different types of total knee replacements.

This paper aims to present the wide possibilities of using the DIC system. The analyses described here would be difficult to perform using conventional contact methods.

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