Smart Biomechanics Strain Measurements using 3D Image Correlation Photogrammetry

John Tyson and Timothy Schmidt, Trilion Quality Systems
Dr. Konstantin Galanulis, GOM mbH

Summary

Biomechanics place huge challenges on existing measurement technologies for determining the mechanical properties of these materials, as well as just measuring the full-field displacement and strain of these materials. 3D Image Correlation Photogrammetry is proving to be a powerful tool for these measurements, providing full-field 3D measurement of the specimens under normal loadings, even at high-speed. This optical technique is independent of the material that it is measuring, providing a non-contact measurement of any material or geometry type. The results are then directly comparable to finite element models for model verification, iteration and boundary condition determination. This paper discusses the theory of the technology, and its application in deformation and strain measurement of real biomechanic and biomimetic applications, from tissues and organs to ligaments and bones.

Introduction

Full-field optical measuring techniques are increasingly being used as measurement tools and for materials inspection. Techniques such as moiré and holographic interferometry (ESPI), for example, have been thoroughly described from the theoretical perspective [1] as well as the application engineering viewpoint [2], [3]. 2D Digital Image Correlation is also being used to get simple inplane deflection measurements. Commercially available 3D optical inspection systems combine exponentially increasing computer power, high-resolution digital cameras and compact mechanical design to provide a robust turnkey measurement capability for industrial, and now for biomedical applications.

There are many reasons to consider full-field 3D measurements, see Figure 1 for a summary of advantages. A single-point gauge cannot show strain gradients, and could miss critical details. This is particularly the case with non-homogeneous and anisotropic materials, typical in the biomechanics world. The 2D results of moiré, ESPI and digital image correlation can only provide simple in-plane deformation measurements. 3D Image Correlation provides the full 3D measurements, which are critical for accurately measuring true strains in these highly 3D materials and loading responses. The final results of optical measurements are compatible with finite element analysis software, and facilitate verification and iteration of models. Perhaps most importantly, measurements that would otherwise be impossible become feasible, opening new avenues of investigation.

The robustness of the 3D Image Correlation technique is shown to full advantage in the following operational situations. The power of 3D Image Correlation provides superior dynamic range and ease of use. Combined with pulsed illumination or high-speed video, it provides unparalleled capability for highly dynamic measurements, such as for in vivo organ studies.

Benefits of Optical Measurements

- Non-contact and Full-Field
- Visualize Strain Gradients and 3D Details
- Test Non-homogeneous & Anisotropic Materials
- Study Tissues and Organs, in vitro or in vivo
- Verify and Iterate Finite Element Models
- Make “Impossible” Measurements

Principles of operation

The material under test is viewed by a pair of high resolution, digital CCD cameras, which measure the sample’s 3D coordinates and the 3D deformations. 3D Image Correlation technology is a combination of two-camera synchronized image correlation and 3D photogrammetry. A random or regular pattern with good contrast is applied to the surface of the test object, which deforms with the object. The deformation of this pattern under the applied load conditions is recorded by the CCD cameras and then evaluated. The initial image processing defines unique correlation areas known as macro-image facets, typically 5-20 pixels square, across the entire imaging area. Each facet center is a measurement point that can be thought of as an extensometer point and strain rosette. These facets are tracked in each successive image with sub-pixel accuracy (to 100th of a pixel). Then, using photogrammetric principles [4], the 3D coordinates of the entire surface of the specimen are precisely calculated. The results are the 3D shape of the component, the 3D displacements, and the plane strain tensor of every point on the surface of the object. An example of a 3D Image Correlation system during a biomechanic tensile test is shown in Figure 1. The camera pair is simply placed in front of the test sample at the calibrated working distance. Because rigid body motion has no effect on the measurements, this type of setup is perfectly adequate for use with servo-hydraulic machines as well as electric screw models, or even in-vivo applications, as we will see.

Figure 1: 3D Image Correlation camera pair on a tripod, ready for measuring of a ligament in a load frame. The ligament is prepared with a stochastically pattern; each macro facet area a separate multi-axial strain gauge. Since rigid body motion is not an issue, the same setup can be used with servo-hydraulic test machines or even in vivo.

The key to 3D Image Correlation is that it tracks changes in an applied micro-pattern (stochastical pattern), rather than a projected pattern, using ordinary white light, and thus does not suffer from the speckle decorrelation limitations of ESPI. The system tracks this stochastic pattern applied to the measurement surface with sub-pixel accuracy. This means that as long as the object remains within the field of view of the cameras, all of the local deformations can be tracked. Thus, large deformations can be analyzed in a single measurement. As previously mentioned, massive rigid body motions have no influence, and can also be calculated from the original pixel registration. In fact, measurements can be continued after a part has been removed, processed and replaced within the camera viewing zone.

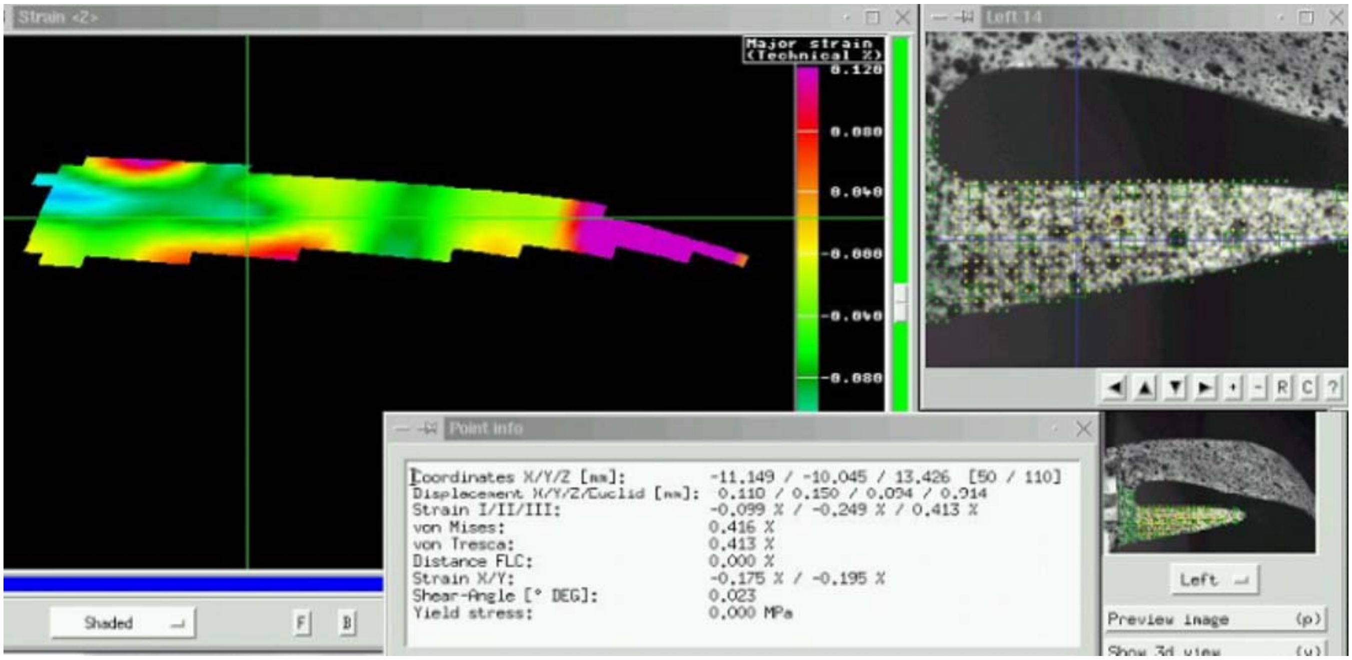
Sensitivity with 3D image correlation is 1/30,000 the field of view. For example, with a 3 cm field of view, sensitivity is 1 micron, and with a 30 cm field of view, it is 10 microns. The system intrinsically measures 3D shape, and therefore 3D deformations are measured simultaneously, rather than sequentially. This significantly improves robustness and accuracy. Furthermore, as will be shown, the use of pulsed high intensity illumination facilitates dynamic deformation analysis. Complete 3D deformation measurements occur at up to 20 Hz or 485 Hz with standard cameras, while higher-speed cameras are also available.

Ionic polymeric artificial muscle

Ionic polymeric materials, are relatively homogeneous and exhibit large dynamic deformations. These biomimetic materials are becoming increasingly important as soft robotic actuators, artificial muscles and dynamic sensors in the micro-to-macro size range. This is used here as an example of a homogeneous material, with similarities to tissues. There is a need to further understand the local strain behavior of such materials, which depends on granular physics and internal water transport, among other effects. [5] This is a perfect application for 3D image correlation.

For this test, the standard measurement cameras were set to run at 20 frames per second, and a sequence of 28 images was recorded for a single flexure cycle. Because of internal recovery mechanisms, these materials function best slowly; the frequency was 0.5 Hz. Intense illumination from a halogen lamp enabled a shutter time of 1 millisecond, which prevented blurring during each exposure. For related cyclic fatigue tests, the cameras can be precisely triggered synchronous with displacement peaks, to ensure capture of maximum strains.

Figure 2 shows one of the captured images. The larger section of the sample tended to collapse beyond the field of view of the cameras, so only the smaller “finger” was analyzed. For subsequent work, the fixturing was controlled more precisely to enable strain measurement on complete samples. The color graphics represent the full-field strain values, together with quantitative results extracted from a single point. Strains were compressive except at the tip, which was moving out of phase. Further analysis using a multi-stage diagram showed profile line strains for numerous flexure stages overlaid. It was seen that there are clearly repeating minima and maxima locations within a single flexure cycle. The final results included a full animation of strains displayed on the 3D deforming shape.



```
Coordinates X/Y/Z [mm]:             -11.149 / -10.045 / 13.426  [50 / 110]
Displacement X/Y/Z/Euclid [mm]:      0.110 / 0.150 / 0.094 / 0.914
Strain I/II/III:                    -0.099 % / -0.249 % / 0.413 %
von Mises:                           0.416 %
von Tresca:                          0.413 %
Distance FLC:                        0.000 %
Strain X/Y:                         -0.175 % / -0.195 %
Shear-Angle [° DEG]:                 0.023
Yield stress:                        0.000 MPa
```

Figure 2: Captured image (right) is of a prepared ionic polymeric muscle sample during a flexure cycle. The larger section flexed outside the field of view in this setup, so only the smaller “finger” was analyzed. Strains were almost entirely compressive at the 19th captured position, except near the tip, which was out-of-phase. A point in the strain window (left) is being interrogated, with the data window showing all of the collected and calculated data for that point.

Tissue studies

Similarly, biomechanics studies benefit from the full-field data, rapid image acquisition and wide dynamic range of 3D Image Correlation Photogrammetry. Experimental analysis of biological specimens have already led to very interesting discoveries, because the complexity of these biomechanics specimens makes them very difficult to model. Beyond the complexities of the biomechanical materials themselves, complex tests, such as biaxial and multi-axial loading set-ups, can be very difficult to monitor with existing techniques. Figure 3 shows a biaxial load test of a nonisotropic tissue sample, a 1” x 1” aorta section. The strain vector flow through the material (displayed) is only possible with this type of measurement. Typical of most biomechanics tests, there is a substantial amount of out-of-plane motion during the test that kills 2D measurement methods such as digital image correlation. A small amount of out-of-plane motion, provides substantial artificial strains, which mask the real strains. This sample curled substantially during the test, making it impossible for 2D systems to accurately track the displacements and strains.

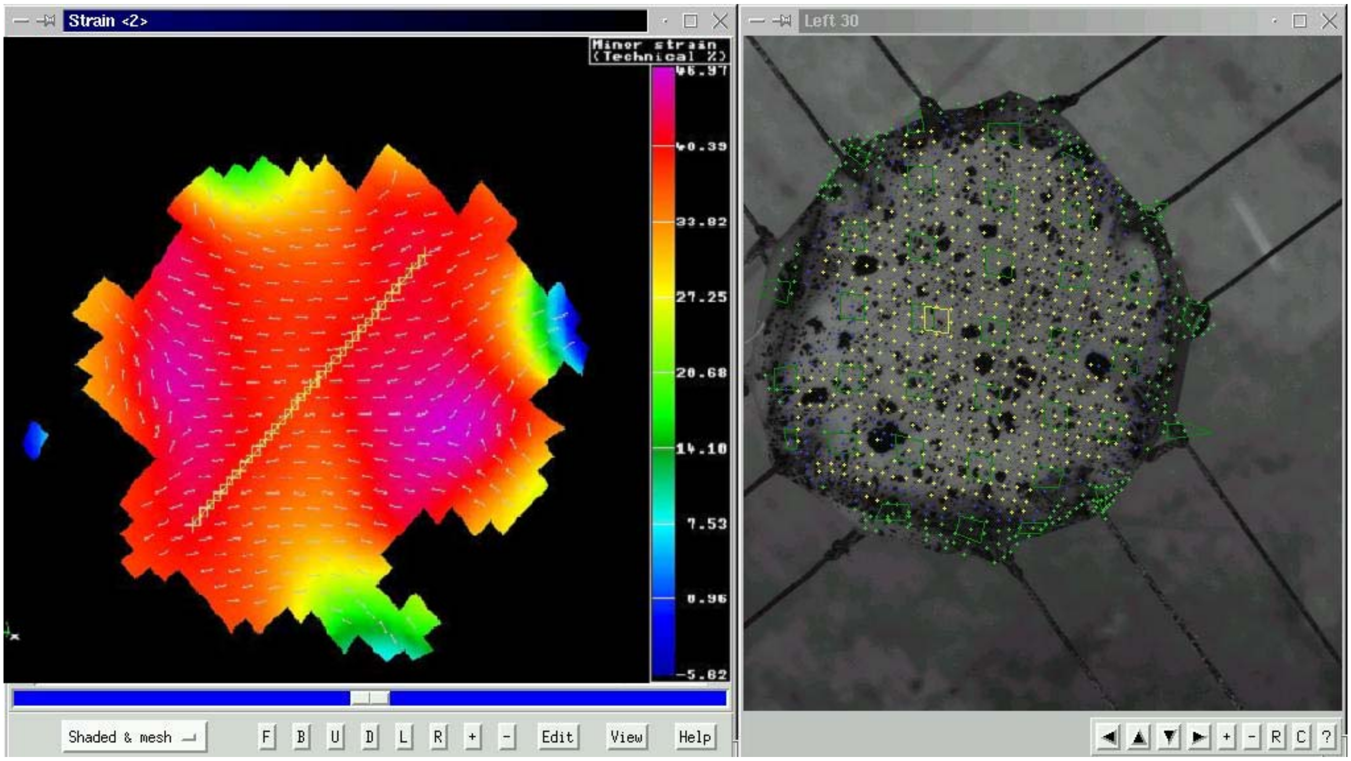


Figure 3: A bovine aorta section under biaxial loading, with axial direction of the aorta is in line with section line and radial direction perpendicular to the line, showing the local vector of the minor principle strain (principle strain 2), the strain flow through the material, uniquely measured by 3D Image Correlation in this highly 3D measurement.

Dynamic deformation measurements of the heart in vivo

The robustness of 3D Image Correlation becomes clearest when dynamic deformations are considered. By using a precision triggering module and stroboscopic illumination, or using high-speed cameras, the system can capture high-speed events. In figure 4, a frog heart was being imaged in vivo. The measurements were synchronized the heartbeat. The displacement data has been overlaid onto the live image of the heart, and an animation of these results showing the heart beating was generated. This was initial work that has led to better understanding of the dynamics of the beating heart and the measurement of organs in vivo. There were displacement transients detected, for which high-speed cameras will be used in a future study to more accurately measure the transient displacements and surface strains. New methods have also been developed from this work to provide a more non-damaging pattern for in vivo organ studies, which also provides a better coverage.

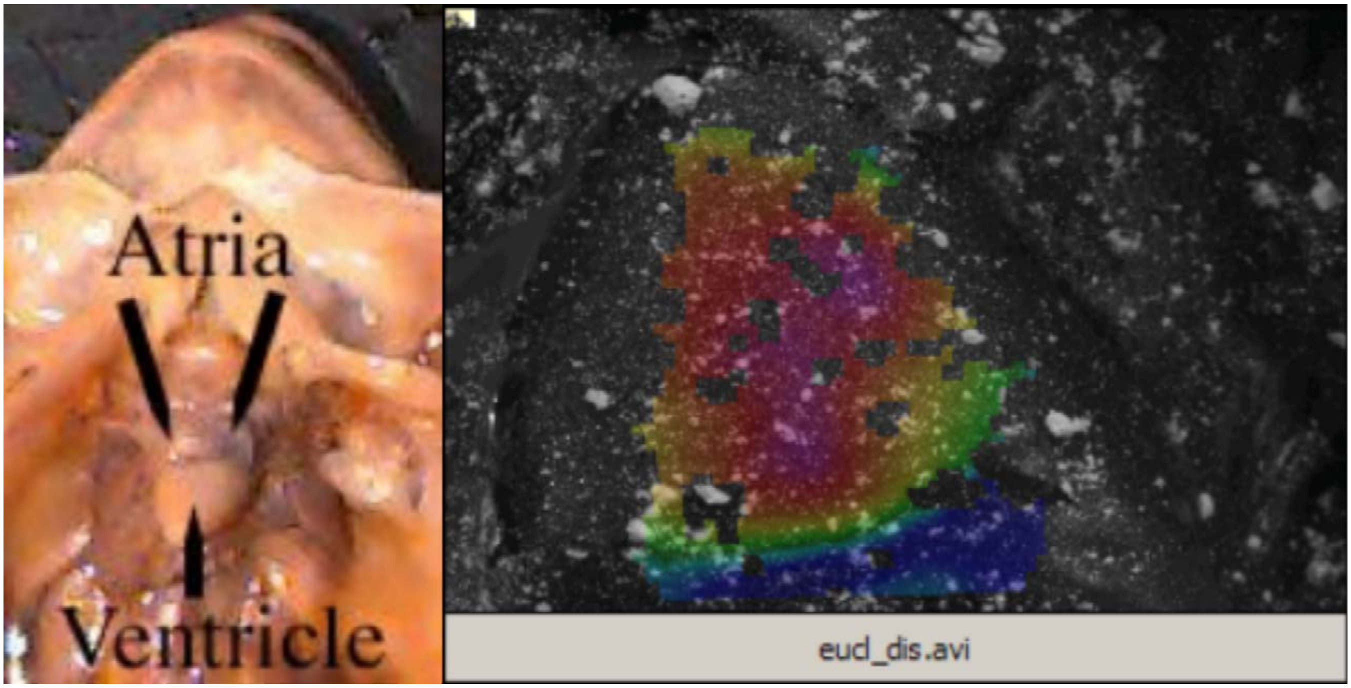


Figure 4: Initial in vivo work of a frog heart had illumination synchronized with the heartbeat. Improvements have been made to the coating technique to provide better coverage and to minimize detrimental effects on the living tissue. It was found that due to various displacement transients, the next work will be done with high-speed cameras to capture all of the transient displacement information of a single heartbeat.

Nonisentropic arterial aneurysm

Taking this capability to solving real biomechanical problems, we studied a programmed aneurysm in a rat aorta. Our test fixture held the aorta and allowed for tensile loading (pulling) and internal pressurization. The tensile loading simulated the actual loading conditions in the body, while the internal pressurization simulated the heart pumping. The aorta was grown with a known aneurysm defect in the vessel wall. The test looked at various loading characteristics of the defective vessel. The initial results shown in Figure 5, show the 3D shape of the vessel rotated for good viewing (right) and the higher strains in the thin sections overlaid onto the real image of the vessel. This work was baselined with silicone rubber tubing and good aortas.

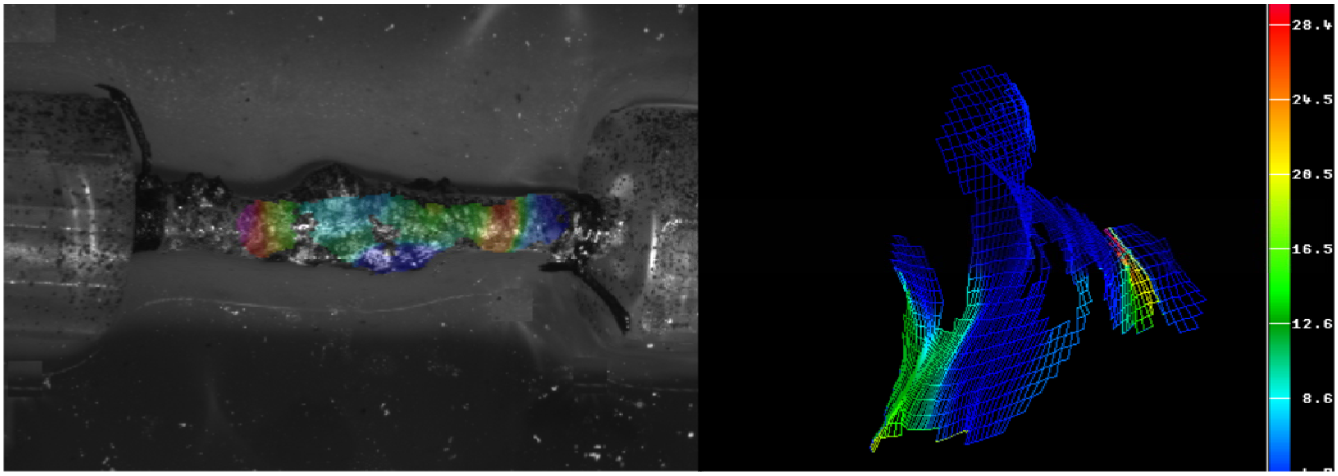


Figure 5 - The study of a rat arterial aneurism, stressed with applied internal pressure, showed strains in the vessel adjacent to the aneurism (left). 3D Image Correlation shows the actual quantitative shape of the aneurism from the side or cross-sectional view (right).

Tendons and ligaments

A typical biomechanical tensile test setup of a ligament is shown in Figure 1. The easily applied stochastic pattern consists of two layers, a white and a black layer. For moist biomechanical specimens, lighting is critical to minimize glare. A preload is often used prior to sample preparation and diffuse illumination can be used. In some high strain cases, only black and/or white speckles are applied to the specimen (without a matte base) and a high-angle axial illumination is used to prevent the glare. Splatter is also an issue with any materials taken to failure. Standard UV (or Skylight) camera filters can be used to take the brunt on any FOD (foreign object damage or flying object damage, in this case). The filters are very cheap as compared to the precision lenses. In the case of the test in Figure 1, a Plexiglas shield was used during sample loading to prevent splatter from local area breakages or premature failure. Typically this shield is removed during imaging to prevent the shield from inducing refractions in the measurement images.

Figure 5 (right) shows the camera view of a tendon specimen during the actual data collection. The inspection area is overlaid with the measurement grid, in which each point represents the center of a macro-image facet. This grid correlates well with the FEM (finite element model) mesh of the computer models. Figure 5 (left) shows a whole-field principal strain result calculated from several load steps. The maximum strain occurred near the bottom of the sample in a bone attachment area, with approximately 12% strain. This dropped to about 2% strain in the tendon itself (top half). From the same data set, the major strain (principle strain 1), minor strain (principle strain 2) and comparable total strains, X,Y,Z displacements and the component shape can be displayed or exported as full-field data.

The bottom section of the sample has much larger cross-sectional area than the top, so it had been expected that strains would be higher at the top. The 3D image correlation system showed in the live video of the test, and the multi-stage loading results, that, due to the non-homogeneous nature of the real tissue, the deformations and associated strains were much higher at the bottom meaty area. Using experimental tests with this optical method, it is possible to see the load transferring across the structure as different components take up the load from other failed structures. This appears typical in ligaments taken to failure, where each fiber of the ligament takes the load at different load levels, straightens out and fails. My own ligament damage takes on a new light.

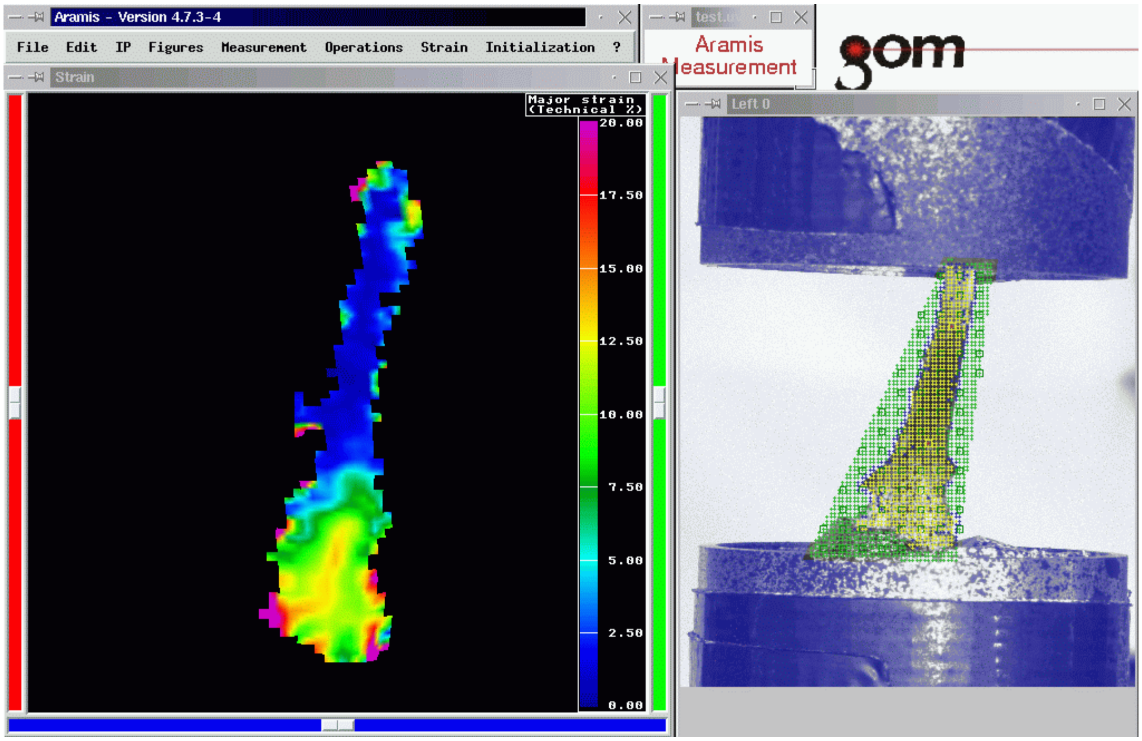


Figure 6: Knee tendon specimen undergoing tensile test. The 3D image correlation inspection area is overlaid as a grid showing each measurement point, which can correlate with a standard FEM mesh. The tendon test result shows principal (major) strains. Strain maxima was unexpectedly found to occur at the thicker section of the tendon specimen. Analysis of deformation throughout the multi-stage loading, presented as a video, confirmed that displacements were much higher at the bottom section.

Conclusions

3D Image Correlation Photogrammetry is a powerful tool for the biomechanics researcher, providing full-field 3D deformation and true strain results from applied loads, not possible with 2D methods. The complexities of the biomechanics samples are so great that theoretical models are difficult to realize. With proper experimental results such as these, statistical material properties can be established, local effects analyzed and resultant models verified.

Not only can the complexities of the materials themselves be imaged and measured, but these studies can be performed either statically or dynamically, with standard equipment or with high-speed cameras, and in multi-axial or other complex loading configurations, as well as in vitro or in vivo. 3D image correlation photogrammetry provides the power and flexibility to meet many of the needs of the biomechanics or biomimetics researcher, and opens powerful new avenues of investigation.

Meet the authors

John Tyson II, PE and Timothy Schmidt are president and vice president of Trilion Quality Systems, in West Conshohocken, PA, USA, a leader in optical inspection technologies, with over twenty years of development and application experience, and can be reached at +1-610-722-5100 or www.trilion.com.
Dr. Konstantin Galanulis is a director of GOM mbH in Braunschweig, Germany, the leader in the development of 3D image correlation systems, and can be reached at +49-531-390290 or www.gom.com.

Acknowledgments

We are grateful to Dr. Mohsen Shahinpoor of the University of New Mexico for the application with ionic polymeric muscle, to Dr. Kurosh Darvish of the University of Virginia, Auto Safety Center, for applications with tendon, ligament and aorta, and to Dr. Ronald B. Bucinell of Union College for the in vivo heart application. All of the results in this paper were obtained using the GOM ARAMIS^{TM} 3D image correlation photogrammetry system; for further details of this and results, including animations (.avi files) of dynamic results, please see www.trilion.com.

References

1) Cloud, Gary, Optical Methods of Engineering Analysis, Cambridge University Press, 1995.

2) Williams, D.C, Ed., Optical Methods in Engineering Metrology, Chapman and Hall, 1993.

3) Tyson, J., Noncontact Full-Field Strain Measurement With 3D ESPI, *Sensors*, Vol. 17 No. 5, pp. 62 - 70, May 2000.

4) Mikhail, E., Bethel, J., and McGlone, J., Introduction to Modern Photogrammetry, John Wiley and Sons, 2001.

5) Shahinpoor, Mohsen and Kim, Kwang J., Ionic polymer-metal composites: I. Fundamentals, SMART Materials and Structures, Volume 10, p 819-833, 2001.

6) Tyson, J., Schmidt, T. and Galanulis, K., Biomechanics Deformation and Strain Measurements With 3D Image Correlation Photogrammetry, *Experimental Techniques*, Vol 26 No 5, pps 39-42, Sept/Oct 2002.

7) R. Kornbluh, R. Pelrine, Q. Pei, and V. Shastri. 2001. Application of Dielectric EAP Actuators, *Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential and Challenges*, ed. Y. Bar-Cohen, pp. 457-495, SPIE Press, Bellingham, Washington.

8) Schmidt, T., Tyson, J. and Galanulis, K., Full-Field Dynamic Displacement and Strain Measurement using Advanced 3D Image Correlation Photogrammetry, *Experimental Techniques,* May/June 2003.