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A method to obtain surface strains of soft tissues using a laser scanning device

Frank Heuer[1], Uwe Wolfram, Hendrik Schmidt, Hans-Joachim Wilke*

Institute of Orthopaedic Research and Biomechanics, University of Ulm, Helmholtzstr. 14, 89081 Ulm, Germany

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Abstract

A three-dimensional laser scanning device was developed allowing surface digitization of musculoskeletal and soft tissue structures under different loads. Image-processing algorithms were formulated for image registration. These were used to determine displacement mapping and then surface strains. Various validation experiments were performed. Accuracy was obtained on a test cylinder after rigid rotation and on a silicon cylinder compressed in four loading steps. The system accuracy (including the scanning and the data evaluation) was $\pm 0.10\%$ strain in vertical and $\pm 0.16\%$ strain in shear and circumferential direction for the rigid rotation exhibiting the zero-strain situation. Silicon cylinder compression showed that the accuracy was best for small strains, whereas strains $>5\%$ evoked a slight underestimation increasing further with higher strains (error of 0.54% for 7.22% vertical strain). It was possible to increase the accuracy by performing the strain measurements via sub-steps. This had a remaining error of 0.41% for 7.22% vertical strain. A further experiment was carried out in order to acquire the surface strain of a human lumbar intervertebral disc while it was forced to flexion and extension.

This study introduced a laser-based scanning method to obtain soft tissue surface strains. It is important to know the strain distribution of musculoskeletal structures and soft tissues. This could help to better understand the mechanical loading of biological structures e.g. the processes in fracture healing. These data could also be used to assist in the validation process for finite-element models.

Keywords: Intervertebral disc bulging; Lumbar spine; Finite element analysis; Validation; Calibration; Image correlation; Phase correlation; Fourier; In-plane strain

1. Introduction

Strain assessment of musculoskeletal structures and soft tissues has been of great interest to biomechanics over the last decades. The quantification of strain along or inside biological structures is beneficial for the understanding, for example the processes in fracture healing (Claes and Heigele, 1999), or how mechanical loading interacts with respect to cell biology (Duncan, 2006; Gilchrist et al., 2007). These strain data are also important for the validation of finite-element models (Helgason et al., 2007). One major limitation still remains that the strain or deformation acquisition was restricted to small measurement locations (Brinckmann and Horst, 1985; Brown et al., 1957; Helgason et al., 2007; Klein et al., 1983; Reuber et al., 1982; Shah et al., 1978; Stokes and Greenapple, 1985; Stokes, 1988; Wenger and Schlegel, 1997).

The three-dimensional (3-d) assessment of soft tissue structures is often very challenging, since most of these structures have complex shapes. Soft tissue exposed to a mechanical load shows further a complex deformation mapping. The interpretation of the deformation by means of simple linear transducers is very difficult and does not fully reflect the 3-d deformation. Three-dimensional strain measurements have already been introduced for trabecular bone using micro-CT scans in combination with image-correlation techniques (Bay et al., 1999; Liu and Morgan, 2007;

*Corresponding author. Tel.: +49 731 500 55301; fax: +49 731 500 55302.

E-mail addresses: frank.heuer@uni-ulm.de (F. Heuer), uwe.wolfram@uni-ulm.de (U. Wolfram), h.schmidt@uni-ulm.de (H. Schmidt), hans-joachim.wilke@uni-ulm.de (H.-J. Wilke).

[1]Also for correspondence: Tel.: +49 731 500 55324; Fax: +49 731 500 55302.

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Verhulp et al., 2004). In contrast, the clinical CT or X-ray techniques are not sensitive enough to render soft tissue geometries and structures sufficiently. In X-ray techniques, it is only possible to obtain soft tissue deformation indirectly via X-ray markers embedded in the soft tissue structure (Costi et al., 2006; Seroussi et al., 1989; Tsantrizos et al., 2005). This method has the potential advantage to provide an internal strain map. Nevertheless, the spatial location of the markers, relative to the tissue, cannot be guaranteed to remain constant throughout motion. Furthermore the insertion of the markers may disrupt the tissue. That means that there could be a relative sliding of the tissue over the markers. Using MRI enables depiction of the soft tissue structure, but with limited resolution and long scanning time. Just recently, a study proposed an image-processing method subsequently MRI scans for determining the internal strains of intervertebral discs (IVDs) (O'Connell et al., 2007). This method provides 2-d strain information along the sagittal plane, but only for axial compression.

The goals of the study were (i) the development and description of a measurement method and (ii) to validate the method for small and large strains. The capability of this method was demonstrated on an exemplary scan of an IVD.

2. Methods

2.1. Laser scanning device

A non-contact laser scanning device was previously developed to perform 3-d surface scans of IVDs (Heuer et al., 2007) (Fig. 1). This system was especially designed to fit in a spine tester (Wilke et al., 1994). Recently, this setup has been improved by exchanging the 1-d laser displacement sensor with a 2-d laser profile sensor (scanControl 2800-25, MicroEpsilon, Ortenburg, Germany). This sensor is capable to obtain profiles with maximal 1024 points per profile having resolutions of 10 μm in radius and 25 μm in vertical direction. Maximum profile sampling rate is 1 kHz. An optical rotary encoder (ZDA-SW14P8G13, Kobold, Germany) was used to determine the position of the rotation stage arm with a resolution of 13 bit (0.04°). A collector ring (SRK72, Columbus, Germany) was mounted between rotational and rigid components to transmit the measurement signals to a mobile computer controlled, custom made data acquisition system. The rotation stage was actuated by a free-from-play belt transmission, which was driven by a DC-servo motor (EC40, Maxon, Munich, Germany) attached to a planetary play-reduced gear (GPL42 K, Maxon, Munich, Germany). The scanner device was controlled by a custom written user-interface program, which also showed the 3-d measurements on-line (Visual C++ 7.0, Microsoft, Seattle, WA, USA).

2.2. Registration and motion capturing

Deformation mapping and strain calculation from images are a standard in image processing. The displacement mapping can be determined by correlating two images, from the unloaded and loaded situation. In addition, registering a motion between images requires distinguishable picture elements, e.g. grayscales, in the form of "salt-and-pepper" noise (Sutton et al., 2000). The data acquired with the laser scanner contain spatial point coordinates of the object surface. They do not provide grayscales, which could directly be taken for image analysis.

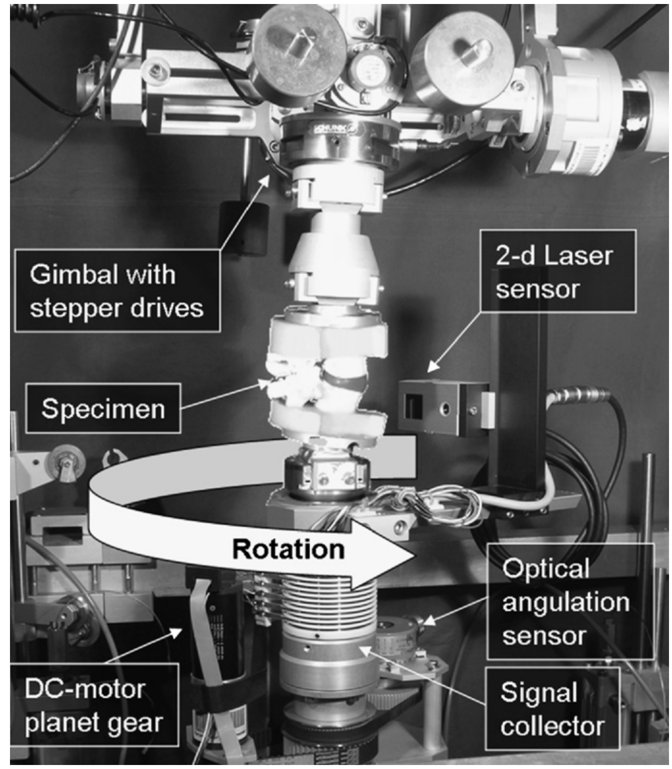

Fig. 1. The laser scanning device can be clamped into the spine tester frame. Specimens can be fixed between the rigid scanner flange and the gimbal system. Pure bending, torsion moments or axial compression can be applied through the gimbal system. During intervertebral disc surface digitization, the scanner rotates about the specimen and records the rotation stage angle and the profile with the 2-d laser sensor.

Nevertheless, it is possible to obtain such a relation between surface neighbor points by computing the second derivate of the surface (Fig. 2).

The artificial surface roughness was generated by coating pepper (*piper nigrum*) with different pigment sizes to the surface, which were stochastically distributed over the region of interest using a pepper mill. The pepper was fixed with high-elastic adhesive spray (Band-Aid, Johnson and Johnson, Germany). Before spraying the glue onto the IVDs, the surfaces were cleaned with a paper towel. It was assumed that the glue did not constrain the measured surface.

Two surfaces (the undeformed and deformed situation) were scanned and assigned to grayscales. Both surfaces were unwrapped to 2-d images by only considering the circumferential and vertical coordinates. Radii data were neglected. Images were sectioned into sub-images having the center points in an overlapping 10×10 pixel grid (Fig. 5). Each sub-image was 61×61 pixels big (called search window). Each search window from the undeformed situation $A(x,y)$ had its corresponding window in the deformed image $A^{d}(x,y)$. The shifts between the two corresponding search windows were determined with the phase correlation method (Kuglin and Hines, 1975)

$$\mathrm{Corr}(x,y) \overrightarrow{=} \Im^{-1}\left\{\frac{\Im(A(x,y)) \cdot \Im(A^{d}(x,y))*}{\|\Im(A(x,y)) \cdot \Im(A^{d}(x,y))*\|}\right\} \tag{1}$$

and

$$[x_{\max}, y_{\max}] = \arg\max\,(\mathrm{Corr}(x,y)), \tag{2}$$

whereas * indicates the conjugated complex of the Fourier transformed of $A^{d}(x,y)$. Search windows were transformed using fast Fourier transformation (FFT). Subsequently, both transformed images were convolved with each other. The inverse FFT of the convolved image yields the integer pixel translation $x_{\max}$ and $y_{\max}$ between $A(x,y)$ and $A^{d}(x,y)$ (Fig. 3).