European Journal of Orthodontics 21 (1999) 413–421

The mechanical behaviour of human mandibles studied by electronic speckle pattern interferometry

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SUMMARY An understanding of the mechanical behaviour of the human mandible during mastication may be useful in several specific medical fields that examine the maxillofacial area. In this research, the Electronic Speckle Pattern Interferometry Optical Technique was applied to study a dry mandible under external stress. Two images of the mandible, i.e. an image of the relaxed mandible and another of the mandible under stress, were processed using this technique and provided information concerning the most stressed areas of the bone. The advantage of interferometric analysis is that it can be carried out in real time on a mandible to which progressively greater stress has been applied. This research may be of value in maxillofacial surgery, for example, in the diagnosis and treatment of fractured mandibles, and in oral surgery and orthodontics, where it can provide information concerning stress dispersion when an osteointegrated implant or orthodontic appliance is placed in the mouth. One of the most important conclusions to be drawn from the experiments of tension, compression, and in- and out-of-plane deformations is that the capability of the mandible to bend is superior to its capability to stretch. Several quantitative results support this conclusion.

Introduction

The structure of the mandible and its complex shape are responsible for its mechanical behaviour when external forces are applied. The human mandible has a spongious internal structure of bone covered by a solid bone wall. This structure ensures that the mandible is resistant to impact, as well as, at the same time, enabling it to transmit muscular force during chewing. Any advances in research with respect to the lines of force dispersion in the mandible, areas of stress concentration, and the weak points of the mandible are potentially valuable from the point of view of possible applications in maxillofacial surgery and orthodontics; for example, in the treatment of fractures and other mandibular damage, in the improvement of orthodontic appliance design and techniques, and also in predicting the effects of an osteointegrated implant.

In order to study the mechanical behaviour of the mandible, it is necessary to measure deformations in the bone when different degrees of external stress are applied. When an external force is applied to a semi-rigid object, its change in shape reflects the direction and strength of that force. These deformations are usually so small as to be only measurable in terms of micrometres and, thus, optical-based techniques are necessary for the purpose. These techniques use the interferometric properties of coherent light (laser) to measure the extent and direction of deformations occurring in an object when a force is applied to it.

Two different optic-based techniques may be applied in the process of this research. They are the holographic interferometry technique (Robillard and Caulfield, 1990) and the speckle interferometry technique (Jones and Wykes, 1989). In the first method, the image reconstructed from the first hologram, a virtual image of the studied object, interferes with the laser light reflected by the real object when illuminated by the same light beam. As a consequence of this interference of light, visible fringes over the image of the object show the microscopic deformations induced after the recording of the hologram. It is possible to observe these interference fringes in real-time, following external loading.

One of the problems of the holographic interferometry technique is that the holographic plates must be chemically developed, dried, and repositioned in exactly the same position as during the original exposure to light. However, if the repositioning of the plates is distorted more than 0.1 μm, any measurement of the deformations will be invalidated. In addition, if any accidental minimal displacement in terms of millimetres in the object is introduced while applying force, all recordings must be retaken or the high spatial frequency of the obtained fringes will not allow for accurate measurement of the deformations. The necessity of repeating the recording many times during experiments and the need for chemical development slow down laboratory work. The necessity for long exposure of the holographic plates (up to half a minute) introduces another experimental problem: any small vibration during the holographic recording occurring due to natural seismology or heavy traffic, will affect the final result. To avoid this problem the use of a specially designed holographic table is required.

The second optical technique, speckle interferometry, can be divided into speckle photography techniques or speckle pattern correlation interferometry techniques. Speckle photography has been used for the study of the biomechanics of the cranium and mandible (Dermaut *et al.*, 1986; De Clerck *et al.*, 1990). This technique also involves chemical development of glass photographic plates and requires posterior optical processing of the recorded images (Dainty, 1984).

The technique chosen for this research was electronic speckle pattern interferometry (ESPI; Jones and Wykes, 1989), due to its technological advantages. The ESPI technique uses a charge coupled device (CCD) video camera connected to a personal computer for the recording of images of the mandible, before and after force application. The CCD camera permits almost immediate recording of the images (one-thirtieth of a second), thus removing the problem of environmental micro-vibrations. There is no need for chemical development of the photographic plates and deformations in the mandible under different degrees of stress are seen in real-time on a TV monitor.

The use of a CCD camera, and a computer to capture and process the images allows the immediate repetition of the experiment, whenever the correlation between images is lost due to accidental displacements of the mandible. The experiment may be repeated any number of times in one session, compared with holography or speckle photography, where only one-tenth of this number of experiments could be carried out in the same period.

Although both holography and speckle photography are based upon the same physical principles, the coherent interference of light, these techniques are different in their methodology and capabilities. Holography provides very clear patterns of fringes, compared with those of ESPI, but it is impossible to directly assess the direction and extent of the deformations. ESPI provides less clear images and the fringe patterns are intrinsically noisy, but it is very easy to obtain quantitative measurements of the deformations involved.

Several authors have carried out research on holographic applications to study the mandible and dentition. Wendendal and Bjelkhagen (1974) studied, *in vivo*, the mobility of teeth when masticatory force was applied on a small sensor placed in the mouth. Other studies have used holographic measurements to investigate tooth mobility in a dry skull (Matsumoto *et al.*, 1985). Dermaut and Beerden (1981) measured limited displacements of bone and teeth after applying Class II orthodontic elastic forces (90–100 g) on a dentate dry skull. Their experiment revealed that prior to any movement of the bony structure of the skull, the teeth start to move and, with increased elastic traction, the stress on the teeth is transferred to the bony structure where the sutures behave as weak points, creating an interruption in the fringe pattern. Ferre *et al.* (1985) and Ferre (1986) also applied holography to the study of dry mandibles under different external forces, obtaining results related to the lines of stress concentration. Dirtoft (1985) employed holography to measure swelling and micro-changes in the shape of dentures.

The aim of this investigation was the application of electronic speckle pattern interferometry (ESPI) with the objective of measuring the mechanical behaviour of the dry mandible.

Materials and methods

Two coherent laser beams, making the same angle with the optical axis objective of the CCD video camera illuminated the cleaned and dried mandible under study. When an object with a rough, non-mirror-like surface is illuminated by the coherent light of a laser, the interference of the light on the imaging system, for instance, an eye observing that illuminated object, will create a speckled light pattern giving an unusual aspect to the object. It will appear to be covered by a multitude of light speckles, hence, the name speckle interferometry. The light intensity of the speckles may be changed under specific conditions, and these changes may be monitored using CCD video cameras and computer image processors. Cyclic changes in the speckle brightness are used to measure deformations on the surface of the object.

Following deformation, the CCD sensors will detect intensity changes in the image. The digital absolute-value subtraction between the image of the object in its initial state, reference image, and the images of the object as external forces are applied will result in an image with dark fringes where no displacement of the object occurs or where the displacement d is equal to:

$$d = \frac{m \, . \, \lambda}{2 Sin\theta}$$

where λ is the wavelength of light, θ is the angle of the illuminating beams with the viewing axis, and m is any integer number (… –3, –2, –1, 0, +1, +2 …).

Bright speckle fringes will show the zones of the object where the displacements are equal to:

$$d = \frac{(2m + 1) \, . \, \lambda}{4 Sin\theta}$$

By altering the angle θ between the two light beams it is possible to change the sensitivity of the measurements. In this experiment the smallest displacements and rotations detectable were 0.4 µm and 1 millidegree, respectively.

Experimental set-up

The optical set-up (Figure 1) used a helium-neon laser as a coherent light source with a wavelength of $\lambda = 633 \times 10^{-9}$ m and coherence length of more than 10 m. The laser was single-line, linearly-polarized with 1 mW of output power. The two coherent light beams were obtained by a beam-splitter, and were collimated using a microscope objective ×25, pinhole filtering and a convergent lens with a focal length of 150 mm. The CCD video camera had a 50-mm objective working with F number 5.6. The sensor area of the CCD was 6.0 × 4.5 mm with a mosaic of 604 × 576 sensor pixels. The area of each sensor was below 9.9 × 7.8 µm due to the arrangement of the sensors. The angle between each beam and the optical axis of the camera was θ = 20 degrees. Under these conditions, the speckle grains had an average diameter of 10 µm. The images captured by the CCD camera were processed by a video frame-grabber board (Model No. DT-IRIS 2851, Data Translation Ltd, Daneshill, Basingstoke, Hants, UK), capable of subtracting the images and showing the results in real time, as the forces were producing deformations in the mandible.

Results

The experimental strategy was based on the study of elemental movements in different sections of a dried and cleaned mandible, in order to show the performance of the ESPI technique on this bone and to provide information for a study of the entire mandible during complex movements.

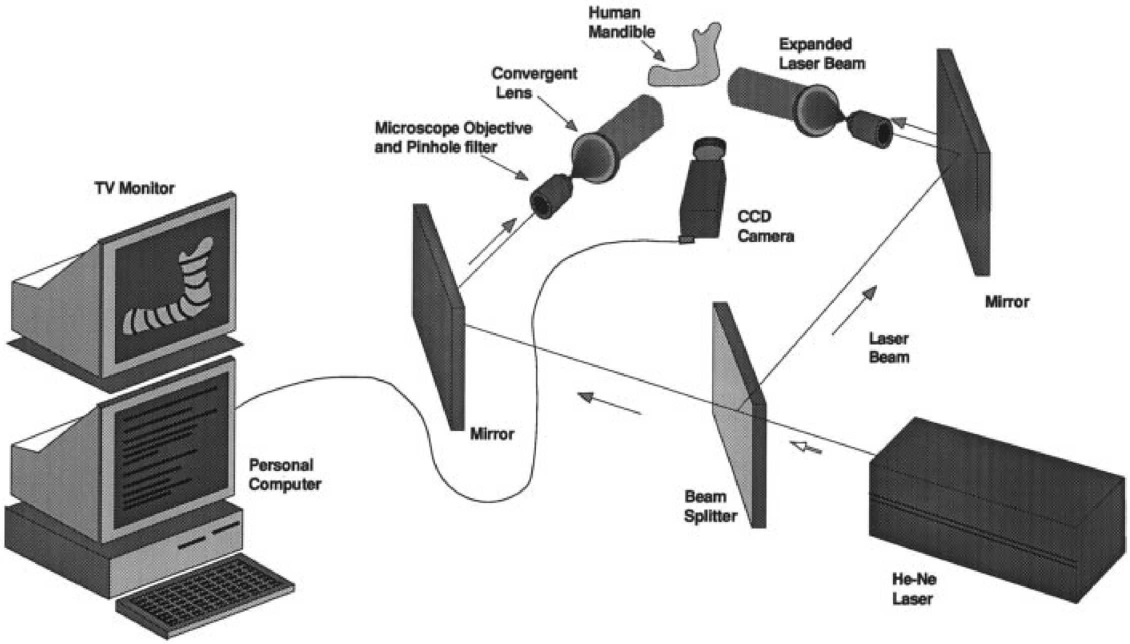

Figure 1 Optical set-up for electronic speckle pattern interferometry (ESPI).

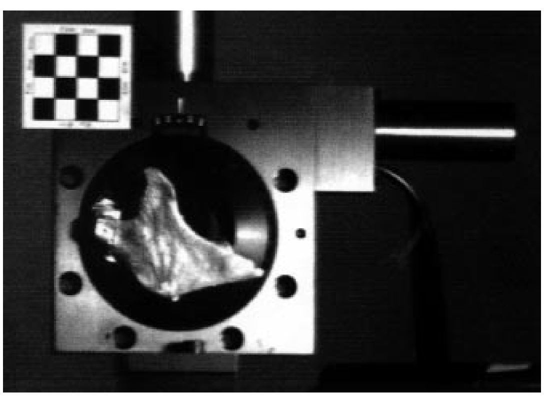

Figure 2 High precision piezo-motor for the experiments of rotation. On the square grid, each black or white square is 1 cm^2.

Rotation

The first mandibular movement studied using ESPI was pure rotation. The mandibular ramus was fixed to a micrometric engine (Model 495-A, Newport Limited, Newbury, Berkshire, UK) capable of producing minimum rotations with a precision of millidegrees (Figure 2). The engine was controlled by a personal computer, which gave a precise reading of the rotated angle. The fragment of the mandibular ramus (4 cm^2) was fixed to a rotating platform using adhesive and rotated at a speed of less than 1 millidegree per second. The aim of this first experiment was to determine whether the bone surface complied with the basic criteria for the use of ESPI; the results confirmed that both the reflective quality and stability of the bone were ideal for the application of this technique.

When pure rotation is studied by ESPI, the resulting image of the object will be one with horizontal equidistant fringes. Calculation of the period of the fringes gives the degrees rotated by the object. ESPI has the capability of measuring rotations with a precision of 10^{-3} degrees. Figure 3a,b shows the reference image of the bone fragment and the image with the fringes after a 10-millidegree rotation. There is no need of further laser processing of the images as with speckle photography, since in ESPI the centre of rotation of an object, obtained with two different directions of illumination, is located where the zero order fringes overlap (Jones and Wykes, 1989).

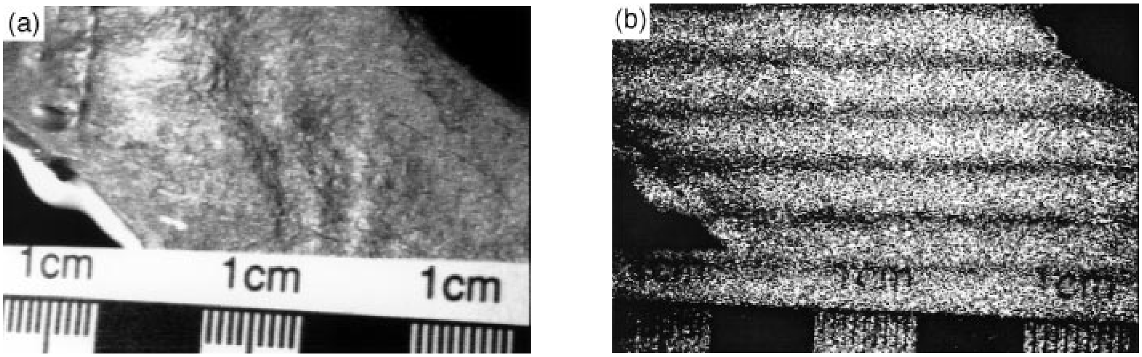

Figure 3 (a) Reference image of the bone fragment before rotation with the piezo-motor, as imaged by the CCD video camera. (b) ESPI fringes pattern obtained after a 0.010-degree rotation of bone fragment. Analysing the spatial period of these fringes it is possible to measure the angular rotation of the bone with a precision of 1 millidegree.

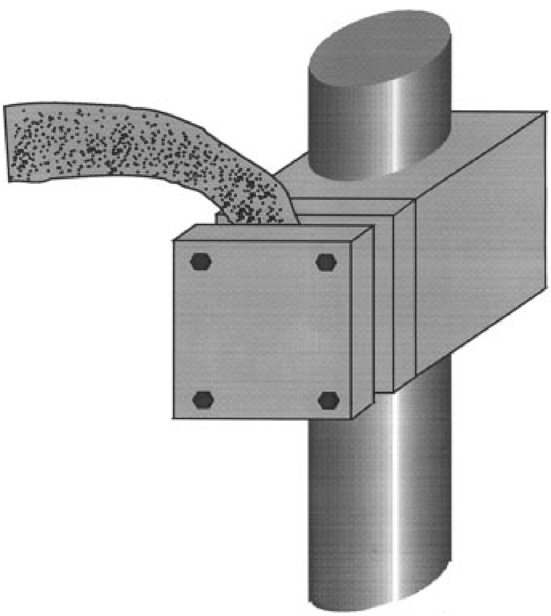

Figure 4 A fragment of the mandibular corpus firmly held using a specially designed holder. Forces in the range of 100 g to 4 kg were applied via nylon threads tied to the free ends of the bone. The deformation of the bone when these forces were applied was measured using ESPI.

Tensile and compressive deformations

A fragment of the mandibular corpus was firmly held using a specially designed holder (Figure 4), which consists of a cylindrical post (Model M-45, Newport Limited), containing in its base an anti-vibration mechanism to avoid distortion or displacement of the images. The bone was tightly held between two blocks of steel and forces, in the range of 100 g to 4 kg acting along the longitudinal axis of the corpus, were applied to the bone via nylon threads tied to the free end. A reference image was produced prior to any force being applied to the bone. This image was subtracted, absolute value subtraction using the computer, from the subsequent images of the bone while traction forces acted on it. The forces were gradually increased from 100 g to 4 kg, with simultaneous observation on the TV monitor to determine the effects of different forces.

The expected result was of an image with vertical fringes, which would show an elongation of the bone in the order of the micrometers. Instead, however, horizontal equidistant fringes of the mandible were obtained in all the experiments. Analysis of these fringes indicated that no tension or compression occurred to the corpus when traction forces in the range of 100 g to 4 kg were applied to the mandible. The conclusion was that in the mandibular corpus its capability to bend was superior to its capability to stretch, it being impossible with the range of forces applied to elongate the mandibular fragment even in the order of magnitude of micrometers. The only visible result of applying traction was a slight rotation of the fragment: the bone minimally changed its curvature, bending in order to disperse the traction or compression forces. This slight change in curvature may be described as a small rotation of the entire fragment around

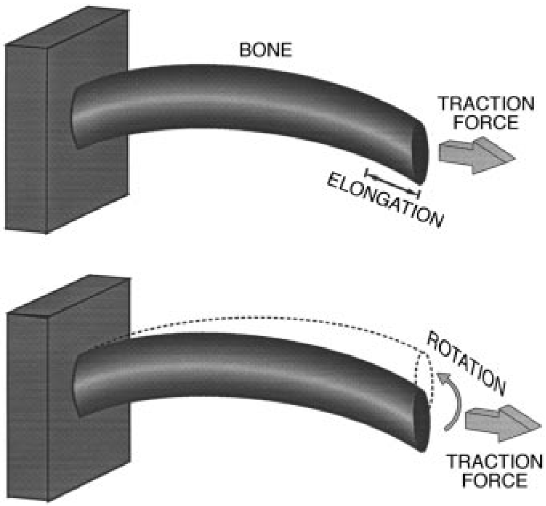

Figure 5 This illustration shows that, instead of elongation, the bone rotated changing its curvature to redistribute the load and the mechanical strain.

the fixed end of the bone (Figure 5). These changes in the curved shape of the mandibular corpus were a consequence of its flexibility, which, in turn, was due to its internal spongious bone structure.

In-plane deformations of the mandibular bone

The dry mandible was fixed with the same stable holder, holding pogonion firmly. Forces in the range of 100–500 g were applied, using nylon threads and weights, to the end of the mandibular ramus, in a vertical direction (Figure 6). The result was horizontal and parallel non-equidistant fringes on the image of the mandible. This fringe pattern changed its periodicity in the zone between ramus and corpus, indicating a zone of bone with a variation in flexibility properties and Poisson's coefficient. When forces were applied, that part of the bone bends, without deformation of the corpus and ramus.

The fringes obtained as a consequence of applying a force of 300 g are shown in Figure 7. The period of the fringes in the area of the ramus was 1.5 times that of the fringes in the area of the mandibular corpus. A quantitative fringe analysis indicated that, due to the weight applied, the corpus rotated an angle of 5×10^{-3} degrees

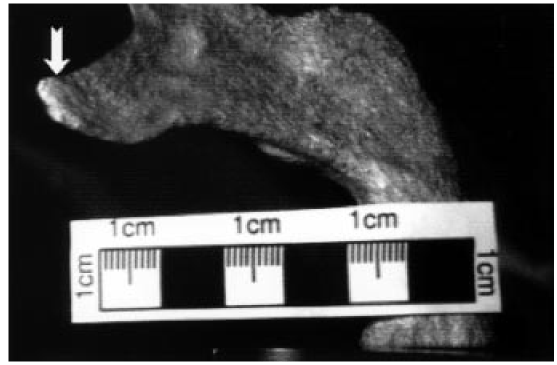

Figure 6 The mandible as imaged by the CCD video camera. The arrow indicates the point and direction where the forces were applied for the in-plane deformations of the bone.

Figure 7 When an in-plane force of 300 g is applied to the bone at the point indicated in Figure 6, the result of the ESP experiments show a pattern of horizontal fringes, which appear over the image of the bone. The spatial period of these fringes changes in the zone between ramus and corpus.

anti-clockwise, while the ramus rotated 7×10^{-3} degrees anti-clockwise. With an increased application force of 500 g, the spatial frequency of the fringes increased, but the same distribution was maintained (Figure 8). Again, the spatial frequency in the area of the ramus was 1.5 times that of the spatial frequency of fringes in the area of corpus. The rotated angles for each fragment were 7×10^{-3} degrees anti-clockwise for the corpus and 12×10^{-3} degrees anti-clockwise for the ramus.

The area where fringe frequency changed was the same in both images, i.e. the intermediate zone between corpus and ramus. The conclusion

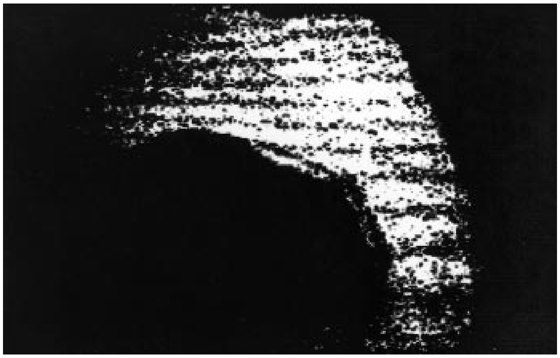

Figure 8 When an in-plane vertical force of 500 g is applied to the bone, the spatial frequency of the fringes increase, but maintain the same spatial frequency distribution between ramus and corpus.

Figure 9 The researcher's hand is seen behind the bone applying force and, simultaneously, the fringes appear in real-time on the TV monitor. The image has been processed by a thresholding process, followed by several dilations in order to improve the fringe visibility.

is that in this zone there is a bone flexing point and an accumulation of mechanical stress.

Out-of-plane deformations of the mandibular bone

The effects of force applied on the mandibular ramus from the inside surface towards the exterior, perpendicular to the bone surface, were examined. Forces ranging between 300 and 500 g, were applied as previously described. ESPI technique is sensitive and will detect extraneous loading of the inside surface of the ramus. The results are illustrated in Figure 9, where the fringes showed areas where equal displacements of the bone occurred as the forces were applied. These were, in fact, lines of iso-elasticity in the bone.

Discussion

The visual display will show fringes moving on the image as more or less force is applied. These images were evaluated on a monitor connected to a computer. One disadvantage of ESPI is that it provides diffuse images and the fringe patterns are intrinsically noisy, although the use of a monitor results in an improved visibility of the fringes is slightly better. This is the reason why the photographs of the fringe patterns are of such poor quality. Although ESPI provides less clear images than holographic interferometry, quantitative measurements of the deformations involved are easier to obtain. All the images can be processed with threshold and dilation procedures, using customized and also commercially available image processing packages.

In this investigation, ESPI was applied to the study of a cleaned and dry *in vitro* mandible, to show the performance of this technique on this bone and to obtain the first ESPI results on the mechanical behaviour of the mandible.

The first experiment consisted of measuring small rotations of the bone by means of ESPI. Using a piezo-engine controlled by a personal computer, rotations in a 4 cm lateral fragment of bone were simulated and measured with a precision of 1 millidegree. The technique demonstrated the capability of measuring rotations of the bone. However, of greater interest is the study of the behaviour of bones under mechanical strain, when they usually rotate around joints between bones or weak points in its structure.

The second experiment performed was to analyse by ESPI the behaviour of the mandibular corpus when it is subjected to forces acting along its longitudinal axis. ESPI is routinely applied as an industrial inspection technique for the measurement of elongations in the order of micrometers. Forces up to 4 kg were applied to the mandible while held in a specially designed holder (Figure 4) in an attempt to induce tension or compression of the corpus along its longitudinal axis. During the measurements with

ESPI, tension and compression of the bone appeared indistinct. Instead, the bone reacted to the forces rotating around the fixed end of the bone. The corpus has a longitudinal and slightly curved geometry. Analysis of bone movement when forces were applied along its axis showed that the corpus, instead of elongating, bends, with a slight change in its curvature (Figure 5). This change in curvature makes the bone more resistant to impact. An impact which would transmit its force along the corpus (e.g. a frontal impact on the chin) instead of compressing the bone, results in bending so absorbing the effect of this impact along the structure of the corpus. This experiment should be repeated using a cleaned fresh cadaverous mandibular bone to validate the result.

The third experiment consisted of applying a force in the mandibular ramus, with the force directed towards the chin (Figure 6). The results with ESPI (Figures 6 and 7) showed that the bone did not bend homogeneously under these forces, but in the zone of bone between ramus and corpus. If an ESPI experiment using a fresh cadaverous mandible shows the same result, this would mean that between the zone of bone there is an accumulation of mechanical strain, and attention should be paid to that zone during orthognathic and oral surgery.

In the fourth experiment, a force was applied from the inside surface of the mandibular ramus towards the exterior. The first ESPI results showed a uniform homogeneous deformation of the bone, without accumulation of mechanical strain in any point.

Conclusions

ESPI has proved able to measure rotations in bone with a precision of millidegrees. Several experiments were performed with a dry mandible using ESPI, and the results indicate that the capacity of the mandible for tension and compression is inferior to its capacity for bending (yielding). As a consequence of the range of forces applied (from 100 g to 4 kg), the mandible modifies its curvature, deviating forces, which could result in a fracture by converting them into relative rotational movements between different zones of the mandibular bone. Future research will study more complex forces and deformations in the mandible, under conditions that simulate mastication, and will also quantitatively measure the elastic coefficients of the bone.

The advantages of ESPI in studying the mechanical behaviour of the human mandible when external forces are applied are:

1. the possibility of studying in real-time the effects of different forces applied to the mandible;
2. the avoidance of the use of photographic plates, so significantly speeding up experimentation;
3. a solution to the problem of a loss of correlation between the reference and subsequent images, as a result of fast acquisition of a new reference image by means of the CCD camera.

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Acknowledgements

The authors wish to thank A. Blanchard for the development of the first image processing programmes used in this research, A. Alonso and J. R. Salgueiro for their kind assistance during the laboratory work, and S. Román and M. P. Dopazo for their support. This research was possible thanks to Xunta de Galicia, Proxecto de Investigacion XUGA 20824B96, and a research scholarship to J. F. Román from the Master in Orthodontics of the University of Santiago de Compostela.

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