Evaluating fracture healing using digital X-ray image analysis

Fracture healing is not easily monitored using currently available techniques.

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A well-defined and consistently quantifiable method to monitor fracture healing is not currently available in the standard clinical setting. Evaluation of the stage and rate of healing is important for predicting ability to bear weight fully as well as for identifying fractures that may be affected by delayed or non-union. It is also important to have a reliable and sensitive way to evaluate fracture healing objectively in the research setting, in order to design useful studies for quantitative evaluation of the efficacy of different treatment methods. Digital X-ray combined with image analysis could provide a simple and cost-effective solution to this problem.

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Traditional methods used to assess fracture healing

Despite the number of people who require treatment for a fractured bone, methods of healing assessment are vague at best. The current procedure that clinicians use to monitor the union of a fractured bone is a combination of patient feedback, manual strength testing and radiography. However, studies have shown that assessment by manually stressing the fracture is a highly inaccurate and subjective method of testing healing strength.[1,2] In terms of radiographic evaluation, medio-lateral (ML or lateral) and antero-posterior (AP) X-ray images of the broken limb at various stages during healing are examined for signs of callus formation and clarity of the fracture line. However, investigations show that plain radiographs correlate poorly with bone strength and are unreliable for assessing the stage of fracture healing or the likelihood of complications.[3,4] Despite its lack of reliability, radiographic assessment is still the primary test used by most surgeons.

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Possible solutions for monitoring fracture healing

Because of the lack of reliability in existing fracture monitoring methods, many solutions, both invasive and non-invasive, have been attempted to improve diagnostic accuracy. Of the non-X-ray based methods, ultrasound and vibrational analysis have shown encouraging results in monitoring the progression of healing bone and evaluating its mechanical properties. However, shortcomings such as lack of reproducibility of measurements and the interference of soft tissue have limited their widespread clinical use and further research is required before they can be regarded as viable clinical techniques. Methods based on radiographic imaging have also been developed to address this problem.

Computed tomography

X-ray computed tomography (CT), especially quantitative computed tomography (QCT), has widely been shown to have excellent accuracy in determining bone mineral density (BMD). Investigators have used this relationship to verify that there is a high correlation between QCT numbers and apparent density in cortical bone over a wide range of densities achieved through distraction osteogenesis, a surgical procedure used to correct skeletal deformities and lengthen long bones. This accuracy has been used for the prediction of fracture risk and may extend to healing fractures, although this has yet to be thoroughly investigated. Despite this potential, the cost and radiation involved in CT, as well as its often restricted availability, limit its clinical appeal.[3,5]

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Finite element analysis

Finite element (FE) analysis has been used to build (largely patient-specific) computer models of bone structure. In general, a three-dimensional (3D) imaging technique such as CT provides geometrical and tissue properties of an object. Further testing provides additional information such as bone mechanical properties so that the model can be used to predict reaction to loads. Models have been shown to agree with observed mechanical behaviour and to be able to distinguish between healthy and osteoporotic bone. However, the potential of FE methods is limited by the large amounts of computing time, high costs and radiation dose associated with intensive imaging and modelling.[6]

Dual energy X-ray absorptiometry

Dual energy X-ray absorptiometry (DEXA) measures BMD and bone mineral content (BMC) and is most often employed for the diagnosis of osteoporosis. Due to its ability to monitor the changing density of bone callus during healing, this technology has also been found by some investigators to be a useful tool for monitoring new bone formation and limb alignment in fractures.[7,8] However, DEXA's inability to measure small changes in BMD, and its decreased accuracy when applied to fractures treated with implants, puts limitations on its clinical use.

Stiffness to monitor fracture healing

A variety of imaging methods to determine the density of the callus in a healing fracture have been reported. However, density *per se* does not relate to mechanical properties and it is therefore questionable how much information a density measure can give on the strength of a bone or fracture site. Another property of bone that has been shown to be a good measure of fracture healing is stiffness. Several investigators have studied this relationship and have found a strong correlation between stiffness and strength, especially in the early stages of fracture healing.[4,9,10]

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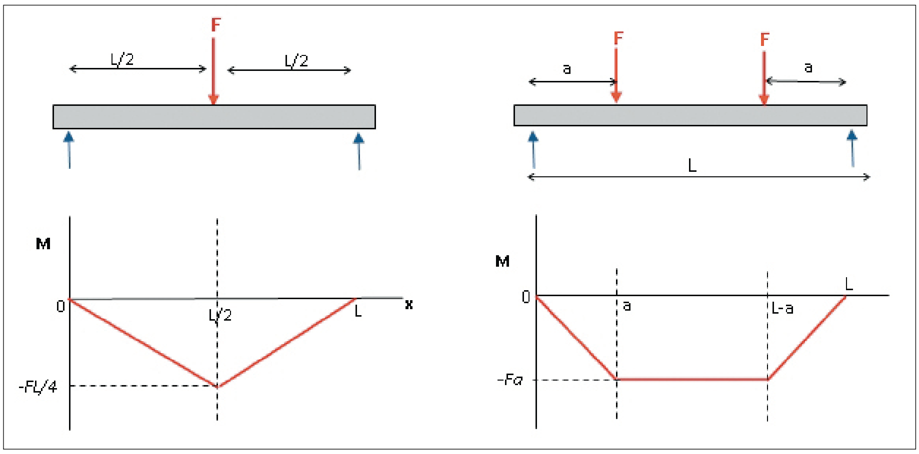

Fig. 1. Schematic illustrations indicating the forces (F) and bending moments (M) for (a) three and (b) four-point bending configurations.

Stiffness can be measured in two ways. The simplest is axial loading, where the specimen is loaded along its axis in tension or compression. Bending tests are also used to determine stiffness, as deformations are often larger and therefore more easily measured. The two common bending configurations are three- and four-point bending. In three-point bending the maximum bending moment is attained at the point where the force is applied, and decreases as distance from this point increases. Four-point bending requires two points of support and two symmetrical points of load (outer and inner fulcra). This results in a constant bending moment between the two points of force application. These types of bending are illustrated in Fig. 1.

The concept of using stiffness to monitor fracture healing has been applied predominantly to tibial fractures treated with external fixators and has been found to be useful in predicting abnormal healing patterns.[1,11,12]

New methods to monitor fracture healing using digital X-ray analysis

Digital X-ray systems are relatively new to the clinical radiography environment. They offer potential in enhancing existing X-ray techniques due to their high-quality digital output in which post-processing can be controlled. If digital X-ray combined with fracture stiffness assessment methods can be used to provide quantitative measurements of fracture healing it could offer benefits in the clinical setting and improve development, testing and evaluation in the orthopaedic research environment.

Radio-stereometric analysis

Radio-stereometric analysis (RSA) is considered the gold-standard method of measuring implant migration using digital X-ray. It uses small tantalum beads, which are inserted intra-operatively. Two simultaneous radiographs are taken at different projections with a calibration cage, and used to provide 3D co-ordinates of the beads. The procedure is repeated over time to allow analysis of movement with respect to the markers. Differentially loaded RSA is a new procedure which has the potential to monitor interfragmentary displacement in fractures due to load, which shows promise in providing objective and quantifiable data to monitor internally fixed fractures.[13,14] However, RSA examinations are time consuming and require invasive surgery, specialised equipment and experienced RSA technicians. These factors add substantial cost and time to the procedure.

Measuring stiffness using digital X-ray image analysis

The previously described methods to measure stiffness have several shortcomings. The first is the need to incorporate equipment that is not readily available, and which is often expensive and cumbersome, into the clinical environment. The second is the common use of a three-point bending configuration, which relies on accurate placement of the

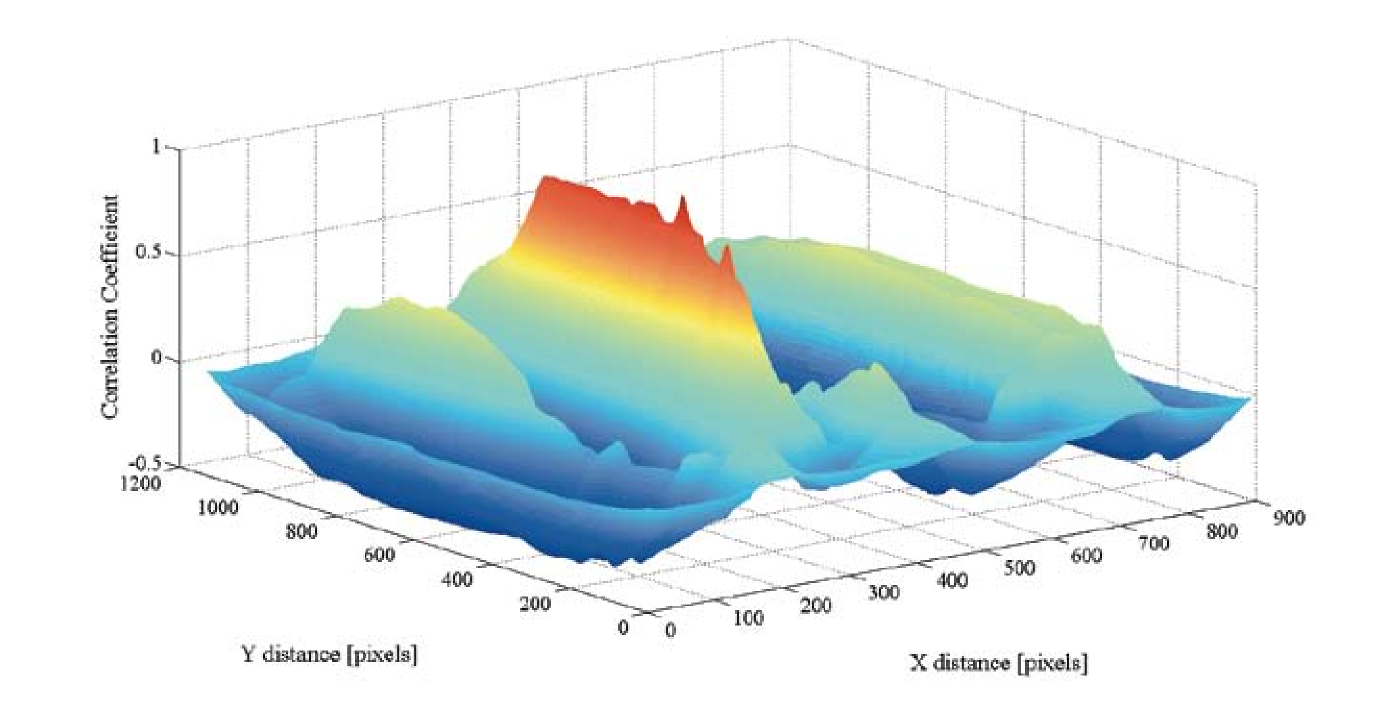

Fig. 2. A cross-correlation plot of two 2D images. The peak in red indicates the XY position at which the images have the best alignment.

force at the point of fracture and, due to patient discomfort, cannot be used in the early stages of healing. Finally, studies have also shown that the uni-planar bending stiffness used in many studies may not detect the weakest plane or be a reliable indicator of fixator removal and that stiffness should be tested in two directions.

A potential method to overcome these limitations is to analyse digital X-ray images of loaded fractures to determine stiffness. A recent study to investigate this possibility used an aluminium frame to apply a four-point bending moment to an intra-medullary nailed tibial fracture during both AP and lateral X-rays.[15]

Computerised procedures were developed to analyse the digital X-ray images of the loaded and unloaded fractures to acquire stiffness information. These were based on cross-correlation, which is a method of determining the similarity between different signals, or, in this case, images. An example for 2D images is shown in Fig. 2, where the peak (indicated in red) indicates the orientation of the images where the result of the cross-correlation is greatest and gives the information required to align two images.

Since cross-correlation can determine the offset between two images, it was used to automatically align the X-ray images of loaded and unloaded fractures. To measure the angular movement induced by bending, the proximal section of bone was selected in the loaded X-ray and cross-correlated with the proximal section in the unloaded X-ray. Since the bone in the loaded X-ray is at an angular offset due to bending, the cross-correlation was repeated while shifting the loaded X-ray in increments of 0.1 degrees until the highest cross-correlation peak was attained. The angle at which this occurred is the angular offset induced by four-point bending.

A slight lateral displacement was also found to occur. To measure this it was necessary to first use cross-correlation to align the loaded and unloaded images according to the proximal segments of bone so that any differences could be measured by comparing the distal segments. The position of the XY cross-correlation peak when applied to the distal segments indicated the lateral offset induced by the bending procedure. An example of a loaded and unloaded X-ray aligned using cross-correlation is shown in Fig. 3. The unloaded image is displayed in the green colour channel and the loaded image in the red colour channel. Where these images align, the image appears yellow due to the colour overlay. Areas where the images do not align due to bending-induced movement appear in red or green.

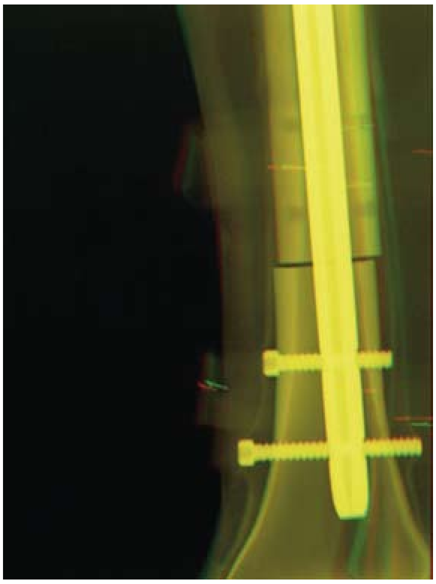

Fig. 3. Colour overlay of two X-ray images of an intra-medullary nailed tibial phantom aligned using cross-correlation.

The four-point bending apparatus and computerised stiffness assessment procedure were tested using models of fractured tibiae to mimic the mechanical environment of a healing fracture and to be visualised using X-ray. The accuracy was 1.5 degrees for angle and 2.3 mm for offset. The procedure was found to be more repeatable than manual measurements.

The feasibility of applying a four-point bending load to fractured limbs during X-ray was tested on a small cohort of 5 patients with fractures of the tibia, who had been treated with an intra-medullary nail. Each patient was followed up at 4 and 8 weeks after surgery. At each follow-up, the patients were X-rayed using the tibial frame. Unloaded and loaded X-rays were taken in both AP and lateral views and analysed. A typical patient set-up is shown in Fig. 4.

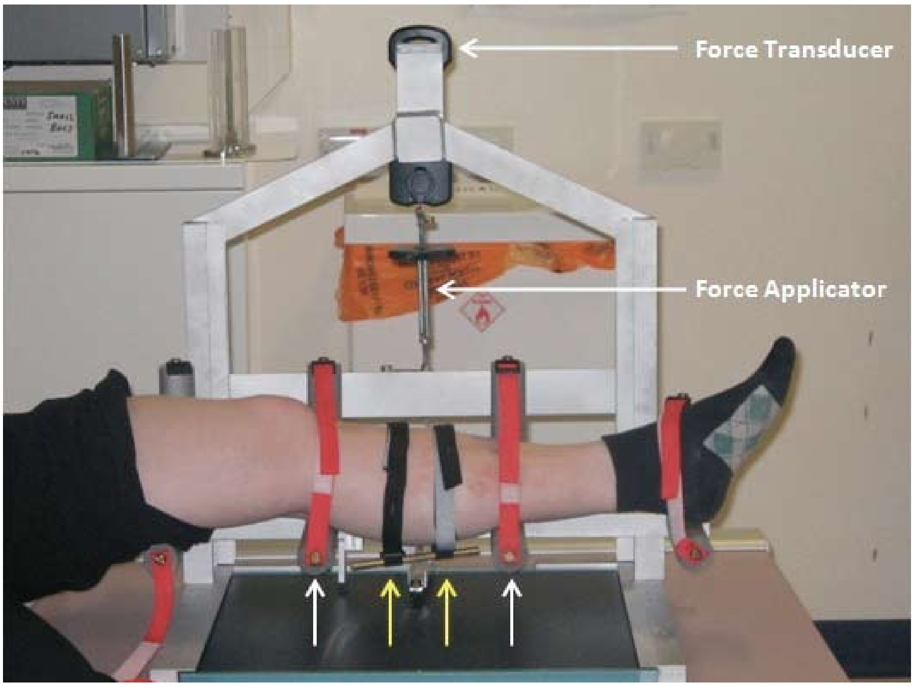

Fig. 4. The four-point bending frame during an AP X-ray of a patient, showing the inner (yellow) and outer (white) fulcra, the force applicator and the force transducer.

The results showed that, although the induced movements were small, the cross-correlation procedure was successful in obtaining angular and displacement measurements for all images. The X-ray frame worked well in the radiography environment and interfered minimally with normal radiographic practice. Furthermore, the frame effectively applied load to the patients and maintained this load during X-ray imaging without the need for any additional radiation exposure to the operator. Patients did not report discomfort or pain during testing.

In order to calculate stiffness information from the measured angular and lateral displacements, it is necessary to calculate the bending moment (M) in Newton-metres (Nm):

$$M = F \times d$$

where F is the force at each point of application and d is the distance between the inner and outer fulcra. The force was measured from the force transducer on the bending apparatus, and the distance was measured directly on the digital X-rays. Following the methods of previous studies, the angular stiffness can be calculated as the bending moment per degree of angulation (Nm/degree) and the lateral stiffness as the bending moment per millimetre of displacement (Nm/mm).[1,11] Repeated measurements of this stiffness information could be used to indicate whether the stiffness of the fracture increases during the healing process, or whether further intervention is necessary.

The apparatus and computerised procedures developed indicate that there is potential for simple procedures using digital X-ray analysis to be used to gain more information on fracture healing. Further development in this area is needed to provide clinicians with an objective measure of fracture healing, using the X-ray equipment that is routinely available in the clinical environment.

Conclusion

Current methods that are used to monitor fracture healing are unreliable and lack the quantitative detail necessary to optimise effective courses of treatment for patients. While there are more advanced and accurate techniques available, these are yet to be validated and are impractical for everyday use due to time and cost implications. Radiographs are readily available, cost effective, non-invasive, relatively harmless, quick to use and, importantly, are familiar to the medical profession. The advent of digital radiography has brought improved image quality and the ability to perform accurate image analysis on X-ray images. Feasibility studies indicate that the measurement of fracture stiffness using digital X-ray image analysis could provide simple and cost-effective techniques for the monitoring and quantification of fracture healing.

Acknowledgements

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References available at www.cmej.org.za

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- Traditional methods of assessing fracture healing are unreliable, while alternative assessment methods can be expensive and time consuming.
- Most fracture assessment methods rely on measuring bone mineral density.
- Stiffness is an important measure of fracture healing and return to function, and has been used to predict fracture healing outcome.
- Digital radiography is used routinely in the clinical environment.
- Digital radiography allows computerised image analysis of digital X-ray images.
- Computerised cross-correlation procedures can be used to measure fracture motion imaged with plain radiographs.