CLINICAL IMPLICATIONS OF STIFFNESS AND STRENGTH CHANGES IN FRACTURE HEALING

MELlick J. Chehade, Anthony P. Pohl, Mark J. Pearcy, Namal Nawana

From Royal Adelaide Hospital and the University of Adelaide, Australia

In the assessment of fracture healing by monitoring stiffness with vibrational analysis or instrumented external fixators, it has been assumed that there is a workable correlation between stiffness and strength. We used four-point bending tests to study time-related changes in stiffness and strength in healing tibial fractures in sheep. We aimed to test the validity of the measurement of stiffness to assess fracture strength.

At each duration of healing examined, we found marked variations in stiffness and strength. Stiffness was shown to be load-dependent: measurements at higher loads reflected ultimate strength more accurately. There was a biphasic relationship between stiffness and strength: at first there was a strong correlation regardless of loading conditions, but in the second phase, which included the period of ‘clinical healing’, stiffness and strength were not significantly correlated.

We conclude that the monitoring of stiffness is useful primarily in assessing progress towards union but is inherently limited as an assessment of strength at the time of clinical union. Any interpretation of stiffness must take into account the load conditions.

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Fracture healing is usually assessed clinically and radiologically in relation to time. This type of assessment of the endpoint of healing for an average fracture of a long bone is satisfactory in only 90% of cases with an accuracy of ± three weeks.1 Many fractures can bear load earlier than their ‘empirical healing time’ and are therefore immobilised for an unnecessarily long period. Others are freed too soon and may sustain refracture or develop malunion after early activity.2,3 A fracture which is sufficiently healed to allow normal sedentary activities may not have sufficient strength for strenuous work or vigorous sport.

The current limitations of methods of fracture assessment has led to much research on alternative techniques. Vibrational analysis4-11 and strain-gauge instrumentation of fixation devices12-17 have been studied to assess objectively the mechanical properties of healing fractures. All these new methods try to measure fracture stiffness either directly or indirectly. In clinical practice, the main aim is to assess fracture strength. Any assessment of risk of refracture by monitoring of stiffness must therefore assume a workable correlation between stiffness and strength.

Our aim was to examine changes in both stiffness and strength in a healing fracture and to test the validity of such an assumed correlation.

MATERIALS AND METHODS

We used 40 skeletally mature, six-tooth (2.5 to 3 years old), Merino wethers. These sheep were randomly allocated to five groups of eight and culled at 2, 4, 6, 8 or 10 weeks. Our model of fracture healing used a left tibial osteotomy after the standardised application of a custom-built external fixator to both legs. A transverse osteotomy was made with a 2 mm thick oscillating saw between the two inner pins of the external fixator placed across the midshaft of the tibia. After operation the sheep were housed in pens and were allowed to mobilise freely.

At the time of culling the external fixator was removed from the left (operated) tibia and both tibiae were excised for mechanical testing, with the right side acting as a control. Mechanical testing was performed with a Hounsfield H25KM Universal Testing Machine (Hounsfield, High Wycombe, UK) fitted with a custom-built four-point bending rig. The tibiae were tested in a mediolateral bending plane; stiffness at the fracture site was determined under both low-
and high-loading conditions. For low-loading stiffness (LLS), the machine’s crosshead was moved at a rate of 10 mm/min until a total load of 150 N was achieved. The specimen was then unloaded at the same rate and this cycle was repeated for a total of five cycles. The stiffness values were determined from the fifth cycle by calculating the maximum slope of the resultant curve of bending moment and displacement. After this, the strength and fail-loading stiffness (FLS) were determined by a further test in which the load was increased at the same rate until the bone fractured. Strength was recorded as the highest bending moment sustained by the bone before failure. The FLS was also calculated from the maximum slope of the bending moment to displacement curve at the portion just before failure.

We also expressed stiffness and strength values as healing ratios relative to the non-osteotomised control bones. We examined the low loading stiffness healing ratio (LLSHR), the fail-loading stiffness healing ratio (FLSHR), and the strength-healing ratio (SHR). These ratios (also referred to as relative stiffness or strength values) were all recorded as functions of fracture healing time. Stiffness measurements were then correlated with strength measurements and correlations were assessed using the coefficient of correlation (r). Significance of differences between groups was accepted as p < 0.05.

RESULTS

Of the 40 sheep, 24 were available for mechanical analysis. Thirteen (all eight of the two-week group and five of the four-week group) could not be tested because of refracture on removal of the external fixator. Of the six-week group, two had fractures through the pin sites of the distal external fixator after falls and one was excluded because of corruption of the computer data file.

Control tibiae. The ultimate failure of all tested control tibiae was always between the inner two pins at the mid-diaphysis of the tibia. The stiffness of control tibiae at the high loads to failure was found to be significantly greater than that measured at the lower loads (mean FLS = 13.9 Nm/mm v mean LLS = 9.9 Nm/mm, p < 0.0001). In the control group the correlation between stiffness and strength was also found to be much stronger when stiffness was measured at higher loads (r = 0.71 v 0.39; Fig. 1).

Fractured tibiae. Testing to failure in the osteotomised tibiae resulted in refracture through the osteotomy site in all cases. The changes in mean fracture stiffness and strength as functions of healing time are summarised in Figure 2. The four-week group was omitted since there were only three surviving tibiae, which biased the group towards the strongest. Wide variations were found within each of the other time subgroups.

Over the ten weeks of the study, normal stiffness was regained much more quickly than strength. Stiffness measured at low loads returned to normal more quickly than that measured at the higher loads to failure (mean LLSHR = 0.95 v mean FLSHR = 0.78 at eight weeks). Over ten weeks, five sheep achieved stiffness values exceeding those of the unfractured control tibiae when measured with low loads, but none of the osteotomised tibiae attained the stiffness of the control leg when measured at loads to failure.

Stiffness v strength. Analysis of the relationship between stiffness and strength suggested two separate healing phases (Fig. 3). For both LLS and FLS the correlation with strength was found to be strong at the lower stiffness values (r = 0.89 and 0.90, respectively). For the higher stiffness values we found no significant correlation (r = 0.00 and 0.44, respectively).

![Correlations of low-load stiffness (a) and fail-load stiffness (b) with strength in the non-fractured control group.](Fig. 1a)

![Comparative mean healing ratios with time (± sd).](Fig. 2)
To obtain a more clinical perspective, the stiffness and strength healing ratios were also correlated (Fig. 4). We found differences in the correlations between relative strength and stiffness which depended on the loading conditions used to determine stiffness. Healing which achieved the presumed prefracture stiffness under low-loading conditions indicated a relative strength of as little as 0.24 (Fig 4a). Under loads to failure, no specimen actually reached the stiffness of the control side although one achieved a relative stiffness value of 0.99. The minimum relative strength at this point, however, was higher at 0.33 (Fig. 4b). Under both low- and high-loading conditions we found a wide range in relative strength, with values as high as 0.62 obtained for relative stiffness values still considerably less than one.

DISCUSSION

Time-related changes. The marked variations in stiffness and strength of healing tibiae at each of the sampled healing times are important. They indicate that clinically applicable ‘normal’ time limits for fracture healing in terms of either strength or stiffness cannot be defined. This variability was despite the use of a standard fracture model in respect to population, mechanism of fracture, and of fixation; this emphasises the poor predictive value of the passage of time as an indicator of fracture healing. For the assessment of fracture healing by mechanical monitoring in the early stages of union, isolated measurements are insufficient; sequential monitoring is required to show progression towards a defined endpoint. The load-dependent characteristic of bone stiffness we have shown also has important clinical implications. The ability of bone to increase in stiffness under heavy load is not fully restored until the later stages of fracture healing. This means that ‘high-load’ stiffness is a more sensitive indicator of fracture healing.

Stiffness vs strength. The biphasic correlation we found between stiffness and strength may represent two histomechanical phases of fracture healing. In the early stages both stiffness and strength result from the same healing process, which is the formation of early woven bone callus with relatively uniform mechanical properties throughout. After this phase, the organisation and remodelling of callus with an increasing amount of lamellar bone may increase...
measurements must take the loading conditions into account. From our data on healing ratio, it appears that the second phase may start when stiffness has reached approximately 65% of the loading conditions. Thus, stiffness increases can potentially monitor changes in fracture strength until stiffness reaches about two-thirds of normal. After this, stiffness can determine only a ‘baseline’ of fracture strength. Stiffness monitoring could only be used to determine an endpoint to fracture healing if the baseline were to indicate a strength that was sufficient for ‘clinical healing’. Stiffness determinations under heavier loads reflect strength properties more accurately and have the advantage of indicating a higher baseline. Even if a baseline for clinical fracture healing could be assumed, there would be insufficient specificity from determinations of stiffness to indicate which bone had attained the greater strength characteristics required for an early return to strenuous labour or high-demand sport. Thus techniques of fracture assessment which rely on stiffness monitoring alone are inherently limited. Richardson et al. have provided clinical evidence that stiffness determinations alone can predict a safe return to independent weight-bearing. They reported no refractures in 95 patients with tibial fractures when the decision to remove external fixation was made solely on the basis of a stiffness endpoint of 15 Nm/degree. None of these patients, however, was allowed to return to sports such as football for six months.

The poor correlation we have shown between stiffness and strength may explain some cases of refractures in clinical practice. When there is clinical healing, patients with tibial fractures are painfree and report a sense of ‘stability’ on full weight-bearing. Despite this, some will have refractures as the result of loads that would appear to be trivial. It seems possible that the proprioceptive signals for fracture stability are related to stiffness. If this is so then the refractures may be in bones which have not achieved adequate strength in spite of ‘normal’ stiffness. This also implies that clinical healing occurs during the second phase of the stiffness-strength relationship, when there is marked variability in fracture strength for a given stiffness. This clinical experience of refracture may be an example of the shortcomings of stiffness monitoring for fracture healing. A more sensitive clinical test for fracture strength may therefore be the patients’ ‘stability sensation’ to controlled higher loads which are still short of failure.

Despite the limitations we have shown, stiffness monitoring remains of value in the early assessment of fracture healing. It can demonstrate progress towards union and thus identify potential delayed or failure of union at an early stage. When clinical healing is suspected, stiffness measurements must take the loading conditions into account. This is not a problem in the early stages of healing when there is a good correlation between stiffness and strength which appears to be independent of the loading conditions.

The assessment of fracture healing by monitoring stiffness is inherently limited but a baseline for fracture healing may be predicted from the inter-relationship between stiffness, strength and minimum functional requirements.

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