Multi-axial Loading Micromechanics of the Cement-Bone Interface

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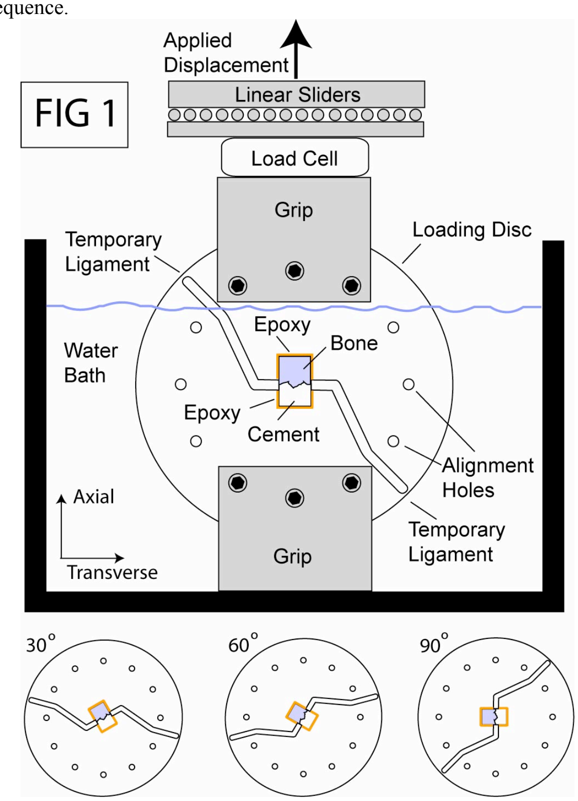
Introduction: There is continued interest in the maintenance and functional response of the cement-bone interface to loads that act across the interface. Recent experimental work has found that the interface is quite compliant (~10 microns/MPa) with sliding and opening occurring from shear and tensile loading conditions, respectively. In addition, this interface becomes more compliant following in vivo service (~50 microns/MPa). The question remains as to whether this micromotion is loading angle dependent. To address this question we performed multi-loading angle experiments on cement-bone interface specimens. We asked three research questions: (1) does interface compliance depend on loading angle?, (2) are there appreciable coupled transverse motions?, and (3) can interface compliance be explained by contact fraction between cement and bone and source of bone (lab prepared or postmortem retrieval)?

Methods: Twelve rectangular prism-shaped (4x9mm cross section) cement-bone specimens were fabricated from laboratory prepared (n=6) and postmortem retrieved (n=6) cemented femoral total hip replacements. These specimens were mounted in custom 'Brazil nut' loading discs (Fig 1) with provisions to load the interface at 0, 30, 60, and 90 deg relative to the cement-bone interface. Non-destructive tests were conducted at each loading angle with cyclic loading applied in tension and compression to specified load limits. Digital image correlation (DIC) was used to quantify interface micromotion during the loading. Interface compliance in the direction of loading (axial compliance = axial micromotion / axial applied stress) and perpendicular to the axis of loading (coupled transverse compliance = transverse micromotion / axial applied stress) were measured during the loading sequence.



MicroCT scans were obtained for all specimens before testing and were used to document interface morphology. A stereology approach was used with a large set of lines projected across the interface in the direction of loading. From this, the contact index (CI) was calculated as the number of points of contact, between the cement and bone, divided by the total number of projection lines that cross the interface.

Results: Axial compliance did not depend on loading angle (**Fig 2**) for laboratory prepared (p=0.96) or postmortem specimens (p=0.62). The coupled transverse to axial compliance ratio, which is a measure of the coupled motion, was small for laboratory prepared (mean (sd): 0.11 (0.11)) and postmortem specimens (mean (sd): 0.14 (0.10)). Using a regression model, there was a moderately strong inverse relationship between interface compliance and contact fraction ($r^2 = 0.65$) with significant contributions from contact fraction ($p<0.0001$), and bone source (lab prepared or postmortem) ($p=0.0017$). Interestingly, for the same contact index, the postmortem specimens were more compliant than the laboratory prepared specimens (**Fig 3**). The cement-bone interface was more compliant under tensile than compressive loading at the 0 deg loading angle only ($p=0.024$).

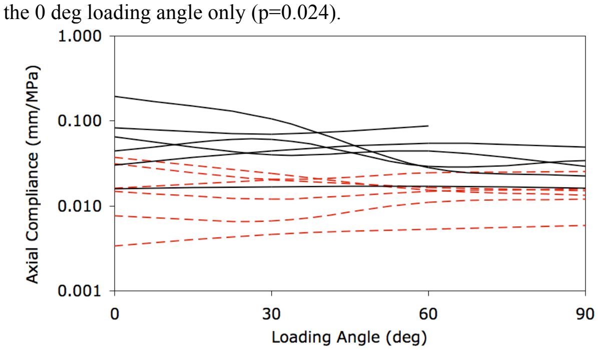


Figure 2: Axial tensile compliance of the cement-bone interface as a function of loading angle for postmortem (solid black lines) and laboratory prepared specimens (dashed red lines).

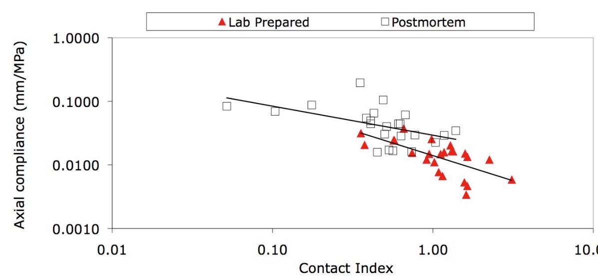


Figure 3: Axial tensile compliance as a function of contact index.

Discussion: The results of this study suggest that interface micromotion from an externally applied load does not depend on the angle at which that load is applied. Further, the coupled motions are small. From a computational modeling perspective, this would support the concept that interfaces could be assigned elastic properties such that local micromotions are isotropic (invariant to loading direction for the same applied stress).

The main limitation to this study is that specimens were not loaded to failure, so that the full failure response in each loading direction was not determined. One approach to generate a full failure response is to perform finite element (FE) simulations to failure of the same specimen with different loading directions [1]. However, FE simulations are also limited by the ability to capture all features of the failure response.

In terms of clinical relevance, these results indicate that interface compliance increases following in vivo service. This is due to a loss of contact between cement and bone. In addition, there appears to be an additional increase in compliance for postmortem specimens for the same contact fraction. The mechanism for this is unclear, but could be due to other changes at the bone-cement interface.

References: Waanders et al, J Biomech, 43(6):1167, 2010.
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