An Adaptable CT-Derived 3D-Printed Alignment Fixture Minimizes Errors in Whole-Bone Biomechanical Testing

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Introduction

Benchtop cadaveric biomechanical testing represents the gold standard for evaluating mechanical properties of bone and developing orthopaedic implants. Virtual tests (i.e. finite element models) can be used for the same purposes, but the validation of such models is critical to their utility. When validating virtual models with physical experiment data, most test configuration parameters (e.g. specimen geometry, applied loads, loading rates, etc.) are well documented and controlled. It is known that differences in specimen alignment during physical testing can introduce unwanted variability in comparative outcome measures, yet standardized alignment methodologies are not well documented. Therefore, the objective of this preliminary study was to design and test the functionality of an adaptive potting fixture that produces precise specimen alignment. This was accomplished using specimen-specific 3D computed tomography (CT) scans of human radii bones. The hypothesis was that accurate specimen alignment using this novel tool would improve the agreement between physical and virtual mechanical tests, while malalignment would introduce errors in the comparison between virtual and physical tests.

Methods

Six radii from 3 donors (1 male, 2 females; 83-89 y.o.) underwent clinical CT scanning in a Siemens Somatom Definition Edge scanner (Siemens Healthcare GmbH; Erlangen, Germany). An axial slice thickness of 0.5 mm was used and a bone density calibration phantom (QRM-BDC/6; QRM GmbH) was included in all scans. 3-D renderings of the radii were segmented using Mimics Innovation Suite v21.0 (Materialise Inc.) (see Fig. 1a-b). The following virtual realignment protocol was used to ensure identical orientation of all models: First, the 3-D location of anatomic landmarks (articular surfaces, styloid process) were defined and a coordinate system was created and aligned with the mechanical axis of the test frame (Fig. 1c). Next, the proximal and distal portions of each radius model were cropped at a depth equal to the widest portion of the distal end. This step was performed to ensure potted bone was not included in the simulations (see Fig. 1d). Tetrahedral meshes were added to each model, and element-specific material properties were assigned by converting radiodensity ρHU (HU) to bone mineral density ρQCT (mgHA/cm3) using the phantom calibration data (see Figure 1.) Finally, Young's modulus was assigned on a voxel-by-voxel basis, using a published density-modulus equation.[1] The aligned virtual models were used to create the specimen specific 3D-printed holders. Specifically, negative molds of mid-shaft geometries were created (Fig 2b), and custom clamps held the bone in place as they were potted in urethane (Master Dyna-Cast, Freeman Manufacturing and Supply, Mount Joy, PA) (Fig. 2c). During testing, both the physical specimens and the virtual models were subjected to controlled axial compressions of 100 N and torsions up to ± 1.5 N-m (physical) or ± 5 deg (virtual remote displacement with calculated moment reaction). Physical testing was conducted on a universal testing frame (TA Electro-Force 3550; Eden Prairie, Minnesota) equipped with a 1,110 N/14.1 N-m load/torque cell. Virtual mechanical testing was carried out in ANSYS Workbench Mechanical (ANSYS Inc.). All virtual models were also tested with deliberate malalignments created by introducing a shift of 13 mm (~ 0.5 in) anterior, posterior, medial, and lateral to the intended aligned axis. In all cases, axial stiffness [N/mm] and torsional rigidity [N-m2/deg] were calculated and compared between physical and virtual models.

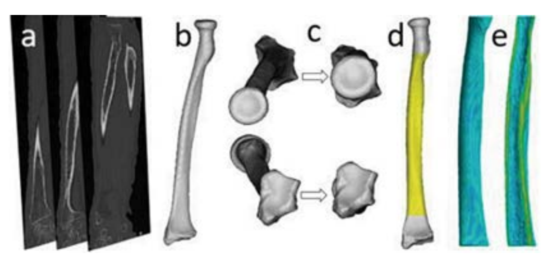

Figure 1. The workflow followed to prepare each radius model for finite element analysis: (a) CT scan image stack (b) Segmented radius (c) Alignment protocol (d) Cropping protocol (e) Element specific material properties assigned (solid body/section view)

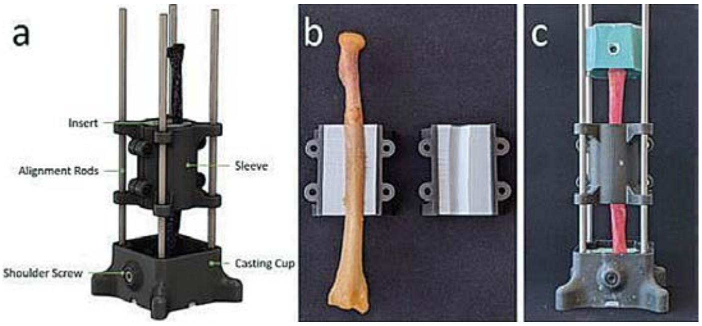

Figure 2. (a) 3D model of the radius alignment fixture indicating critical fixture components. (b) Patient-specific 3D-printed insert positions radius in the same orientation as in the virtual model. (c) Radius alignment fixture with an aligned cadaver radius fully potted.

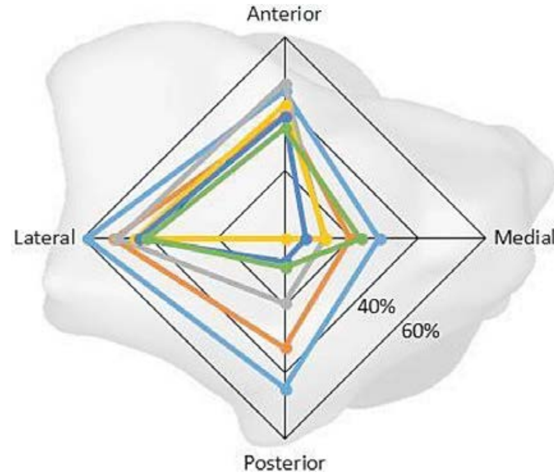

Figure 3. Distal-to-proximal view of an aligned radius. Radar chart illustrates the average percent error relative to the aligned condition for all six radii virtually tested under malaligned conditions. Axial stiffness was highly sensitive to malalignment, whereas torsional rigidity was not.

Results

For all six radii tested with identical specimen alignments achieved through the use of the CT-based 3D-printed fixture, a strong and statistically significant correlation between the physical and virtual test results was observed (axial stiffness: $R2 = 0.756$, $p = 0.031$, torsional rigidity: $R2 = 0.986$, $p < 0.001$). The physical samples could only be potted once, so for comparison, deliberate malalignment was introduced into the virtual models for all specimens. Comparing these anterior, posterior, medial, and lateral offsets to the perfectly aligned scenario resulted in 39.2%, 16.8%, 18.8%, and 48.1% average percent errors, respectively, in the axial loading condition (see Fig. 3). The off-centered torsional loading conditions resulted in 1.8%, 1.0%, 1.7%, and 1.4% average percent errors, respectively.

Discussion

As hypothesized, small specimen malalignments of 13 mm between the intended aligned axis and machine test axis caused significant errors in measured axial stiffness of the virtual bone models. Torsional rigidity measures had higher correlations to physical test results and were robust to deviations from ideal alignment, with errors less than 2% in all directions. This suggests that, whenever appropriate, torsion tests should be used preferentially as a summary mechanical measure, or as a supplement to axial compressive tests. When more challenging modes of loading are required, pretest clinical-resolution CT scanning can be effectively used to create potting fixtures that allow for precise specimen alignment. In some applications, this may be important for increasing the correlation and reducing the error between physical and virtual mechanical tests.

Clinical Relevance

CT scans are increasingly being used to assess bone quality in biomechanical research. Opportunistic use of these scans together with additive manufacturing techniques allows for fabrication of adaptable specimen potting jigs that guarantee the desired sample alignment and reduce omechanical testing errors from alignment artifacts. This may be particularly important for more sensitive biomechanical tests (e.g. axial compressive tests) that may be needed for industrial applications, such as implant design.

References

1. Morgan, E.F., Bayraktar, H.H., Keaveny, T.M., 2003. Trabecular bone modulus-density relationships depend on anatomic site. *J. Biomech.* 36, 897-904.