Calcaneal Fixation Plate Test Method Development

Dana J. Coombs, MS, Michael Bushelow, MS, Sherri Wykoski, BS.
DePuy Synthes, West Chester, PA, USA.

Disclosures:
D.J. Coombs: 3A; Employee of DePuy Synthes. **M. Bushelow:** 3A; Employee of DePuy Synthes. **S. Wykoski:** 3A; Former employee of DePuy Synthes.

Introduction: Standard ASTM test methods, such as four point bend tests based on ASTM F382, do not apply well to fixation plates with complex geometry and loading. The objective of this study was to develop a test method using typical mechanical testing equipment what would closely simulate the musculoskeletal loads on the calcaneous bone during gait. This study used a validated, detailed musculoskeletal model of the foot to determine muscle, ligament, and joint contact forces during gait, to develop a better validated test method. A Sanders IIb fracture pattern was used for this study.

Methods: The AnyBody Modeling System (AnyBody Technology, Aalborg, Denmark) Foot Model was used to estimate the loads applied on the calcaneous bone during the stance phase of a healthy person's gait. The foot model contains all the individual foot bones, muscles, and major ligaments. It was developed using data from literature about joints' type, position and orientation, as well as muscles and ligaments' attachment points and mechanical properties. The model was also validated by comparing EMG measurements to predicted muscle activation for 8 subjects. The calcaneus bone receives loads from various mechanical structures:

• Two joints; subtalar joint and calcaneo-cuboid joint.
• Muscles: Gastrocnemius, Soleus, plantaris, Extensor Hallucis Brevis, Extensor Digitorum Brevis, Quadratus Plantar, Abductor Hallucis, Flexor Digitorum Brevis, Abductor Digiti Minimi
• Ligaments: Tibiocalcaneal, Calcaneofibular, Calcaneonavicular, Calcaneocuboid Plantar and Dorsal, Bifurcate, Long Plantar and Plantar Aponeurosis.
• Floor: A force plate and pressure sensitive plate measured the reaction force and the plantar pressure distribution, which was applied to the bone.

The subject, used for this model, weighed 76 kg and had a foot length of 235 mm. The motion capture data was imposed on the model. A series of force vectors were applied to a grid on the surface of each bone according to the recorded pressure distribution based on the force plate and pressure plate. The output of this analysis was Abaqus (Providence, RI) input files, which contained all loads in the model as a function of gait time. Figure 1 shows the load inputs and muscles activated during gait. ScanIP (simpleware, Exeter, UK) was used to process the tessellated (.stl) file for the subject's calcaneous used in the musculoskeletal model. ScanIP was also used to model the fractures representing a Sanders IIb fracture pattern. An Abaqus mesh of the calcaneous was generated using the +FE Free mesh algorithm.

Synthes 3.5mm Locking Calcaneal Plate (241.622) and Synthes 3.5mm, self-tapping, locking stardrive screws were assembled to the calceanous in Abaqus CAE. The plate and screws were meshed with C3D10 quadratic tetrahedral elements. The mesh density was defined such that a minimum of 2 elements were defined across the flat side walls of the plate. The screw body was constrained to the mesh of the bone and the screw locking screw head was constrained to the plate hole. The plates and screws used a material model which represented stainless steel (E = 186400 MPa, ν = 0.3). The bone material property was stiff enough to transfer loads to the plate and not deform grossly (E=20000 MPa, ν = 0.3). The model was run using the Abaqus Standard implicit solver.

The results of the analysis determined that the greatest stresses in the plate occurred at "toe off" (1.191 seconds) during the stance phase of gait, using maximum principal stress, as shown in Figure 2. The internal loads and moments in the plate were determined every 3mm along the length of the plate using Free Body Cuts in Abaqus CAE and graphed along the length of the plate.

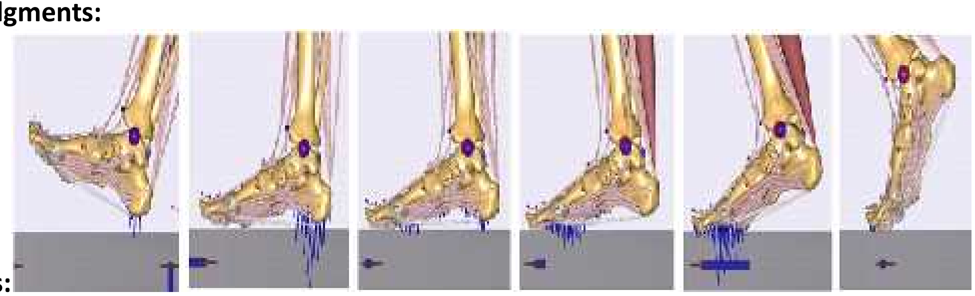
Upon examining the data, it seemed possible to reproduce these internal forces and moments by using a 3 point bend configuration for the forces and moments in the plane of the plate. Generally, the inferior/superior direction shear loads have a step and moments plate plane have a linear increase and decrease. The shear load step and the moment inflection occur at the same location, which matches a shear and moment diagram for a 3 point bend configuration. To determine a 3 point bend test configuration, the internal Free Body Cuts shear and moment were used to create free body diagrams to determine the location of supports and direction of applied loads. The initial assumption was that this was a planar problem and the left and right side support is a simple pin support. Summation of forces in the two directions in the plane of the plate and summation of moments in the plane were equated to zero for static equilibrium.A second finite element model was developed, using Abaqus CAE, to simulate the three point bend test method, based on the support locations and input load values and location determined from the free body diagrams. The same element types, mesh density, and material models were applied. The locking screw head was constrained to the plate holes. Reference points were defined at the location of the supports and the input load. Constraints were applied to simulate rollers on the support points. A load was applied to the input load point. The input load point was moved 25mm out of the plane to create out of plane bending to better match the musculoskeletal model. The maximum principal stress seemed to be a good qualitative match to the musculoskeletal results. Finally, the test blocks were designed and added to the model. The test blocks material models were defined as Objet VeroWhite (E = 2500 MPa), which is used by the Objet 3D printer. A reference point was created at the center of the left pin hole and another at bottom surface of the right test block at the right roller location. The constraints were similar to point load model. A third reference point was created at the center of the concave spherical cut, which is where a ball would apply load through the actuator. The reference points were connected to the test blocks using tie kinematic coupling constraints. Figure 3 shows the design of the test setup.

Results: Qualitatively, the maximum principal stress distribution matched well, as shown in Figure 4. However, the stresses in the test method model are lower. Three main factors could explain this result. First, the plate was modeled as planar and not bent to fit the calcaneous. Second, the test blocks were not rigid to match the point load model. Finally, the boundary conditions are not exactly the same. The right support pin does not match the boundary conditions of the point load model. However, these boundary conditions were determined based on a feasible test setup. The stress results exceed the yield strength of the stainless steel material. It is not assumed that someone would apply normal gait loads with a fractured calcaneous even with fixation. The magnitude of the input load would be less for actual mechanical fatigue testing.

Discussion: The goal of this study was to determine a test method that would reproduce the musculoskeletal loads on a calcaneal fixation plate based on the stress distribution. A three point bend test method, which includes offset loading to create out of plane bending, can be used to replicate the musculskeletal loads. The comparison is based on a qualitative comparison of the stress distribution in the calcaneal plate.

Significance:

Acknowledgments:



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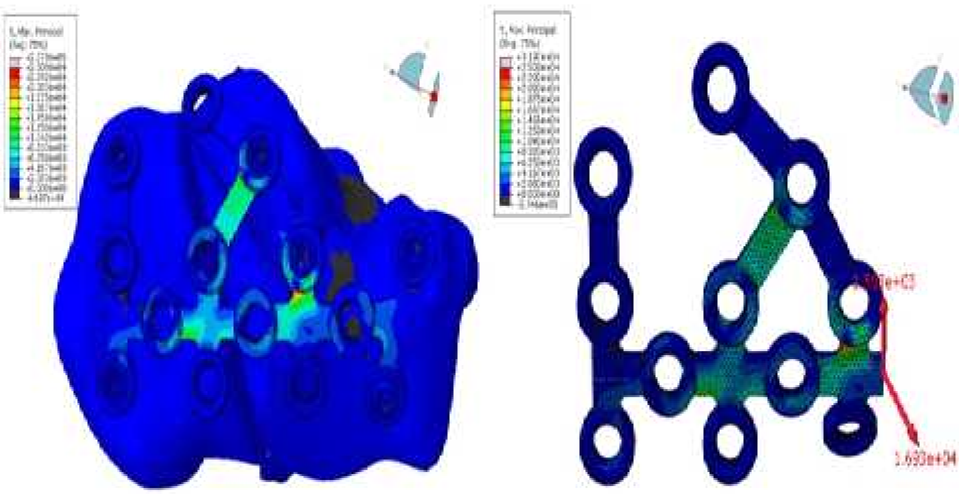

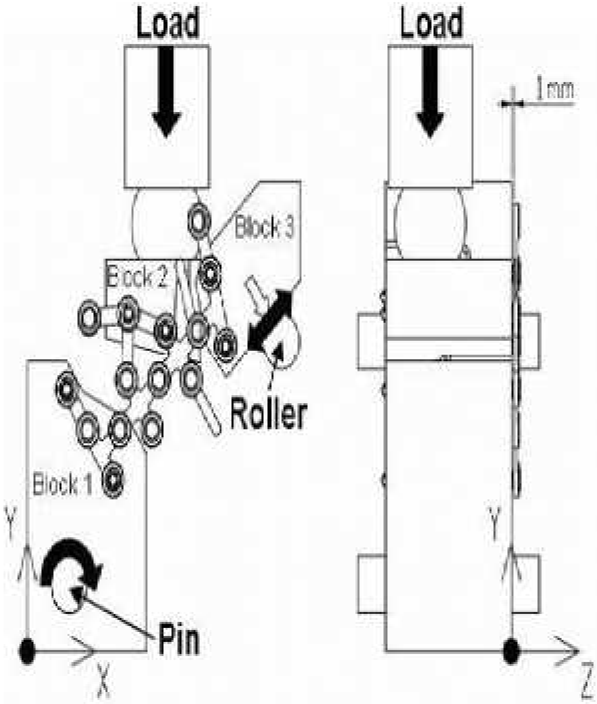

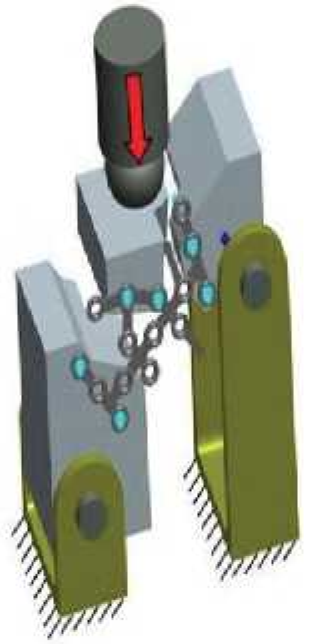

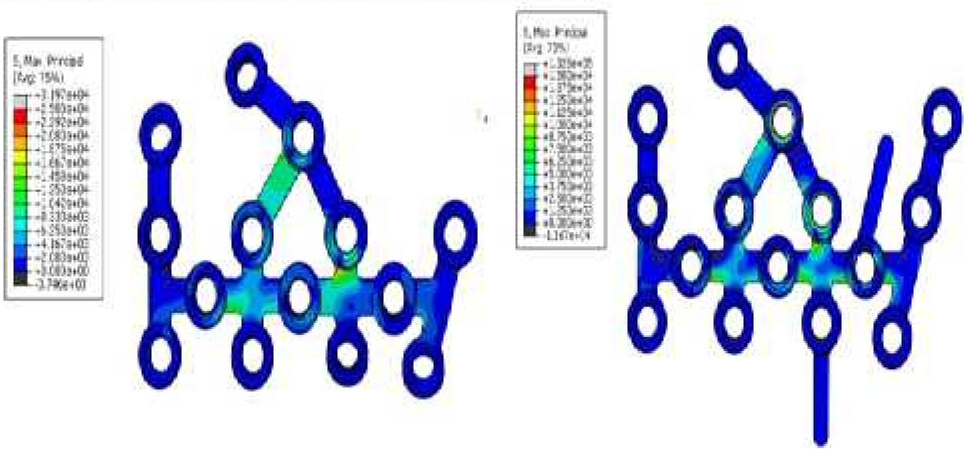

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