INTRODUCTION
High-resolution image-based micro finite-element modeling (µFE) is a valuable tool for estimating bone mechanical alterations due to disease or drug intervention [1, 2]. The method typically entails solving large-scale complex systems with 10-100 million elements, thereby requiring significant computing resources in terms of memory and computation speed, limiting its practicality in the clinical setting. Here we describe a computationally efficient µFE solver with the objective of running large-scale µFE simulations on desktop PCs or standard workstations. The performance of the µFE solver is illustrated with applications to human specimen micro-CT (µCT) and in vivo high-resolution MR (µMRI) images as input into the model to estimate stiffness and failure load as well as an intact femur comprising over 10⁸ finite elements.

METHODS
µFE Model input: High-resolution images provided by advanced imaging technologies, e.g. µCT, µMRI and HR-pQCT, are utilized in our µFE modeling to generate 3D grayscale arrays, the inputs to the µFE solver. These grayscale arrays are referred to as bone volume fraction (BVF) maps, where each voxel value represents the fractional bone occupancy at the individual voxel, ranging from 0% (pure marrow) to 100% (pure bone). To set up the model, each voxel on the BVF map occupied by bone is directly converted to a hexahedral finite element of equal size. The bone tissue material properties are assumed to be linearly elastic and isotropic. Hence Young's modulus (YM) for each element is proportioned to its BVF value as YM=(BVF) x 15 GPa while Poisson's ratio is held constant at 0.3.

µFE Model structure: Our µFE modeling for bone mechanical properties involves three steps: (a) applying a small macroscopic strain to the structure (e.g., compression), (b) computing the resultant displacements throughout the structure by solving a linear system, and (c) calculating the resultant stresses on the surfaces of the structure.

µFE Model kernel: A system of linear equations based on the stress-strain relationship is established by minimizing the total elastic strain energy over the entire structure and solved for the unknown displacements. Although the linear system is sparse, memory requirements can become prohibitive if the entire coefficient matrix is stored, especially for large-scale problems. This problem can be greatly mitigated via an element-by-element (EBE) approach to the µFE simulation algorithm, which avoids assembling and storing the entire coefficient matrix. The memory usage can thus be reduced by over one order of magnitude. A parallel preconditioned conjugate gradient (PCG) iteration method was utilized and a pre-iteration on coarser grids strategy was applied to save computation time. Finally, a log-derivative convergence criteria is needed for residual computations.

µFE Model execution: Figure 1 illustrates the processing steps when applying our µFE solver to estimate bone mechanical parameters in distal tibia using µMR images. First, signal variations in the µMRI images were corrected. Then the tibial TB and CB regions were segmented, normalized and inverted to obtain the BVF maps. Last, µFE simulations were applied to either (1) the whole TB and CB regions or only the TB region for whole-section axial stiffness; or (2) an extracted subvolume for estimating the six elastic moduli.

RESULTS AND DISCUSSION
Computation time: Figure 2 shows plots of average computation time per iteration versus number of elements for different numbers of threads: one, two, four, and eight respectively. If 600 iterations (which was estimated using our log-derivative convergence criteria) are needed for simulating a system with 20-million elements, we found that parallel computing using eight threads can bring the computation time down to ~0.6 hours (compared to ~3.9 hours using a single thread). Further, all in vivo µMR or HR-pQCT image-based µFE simulations (which usually have less than 5 million elements) can be done on desktop PCs (with 4GB of RAM) in 10 minutes using our solver, compared to currently on commercial PC-based systems 3 to 5 hours in [4]. A typical µMRI image set at the distal tibia or radius comprises about 500,000 elements requiring less than 1 minute computation time.

Large-scale problem application: The µFE solver was utilized to estimate stiffness and failure loads in the specimen of a human femur µCT image at 80-micron voxel size. A sample slice of the simulated strain-energy map in coronal view is given in Figure 3. Simulated compression was applied to the top surface of the femoral head (simulating loading in stance) through fictitious cap encompassing the top of the femur head. The total number of elements in the µFE model was 90.3 million and the total time for solving the resultant linear system was 8.3 hours on an 8-thread laboratory computer (dual quad core Xeon 3.16 GHz CPUs equipped with 40 GB of RAM). Applying the ‘pre-iteration’ approach further reduced the computation time to approximately 4 hours. A similar study reported previously required a total computation time of about a week for a system with ~97 million elements [5].

CONCLUSION AND SIGNIFICANCE
A computationally efficient system was developed for image-based µFE computational bone mechanics. This program enables large-scale simulations on standard PCs or workstations within practical computation times previously only achievable with supercomputers.

REFERENCES