A NEW QUANTITATIVE IMAGE-BASED ATLAS OF HUMAN FOOT BONES IN DIABETIC FOOT DISEASES

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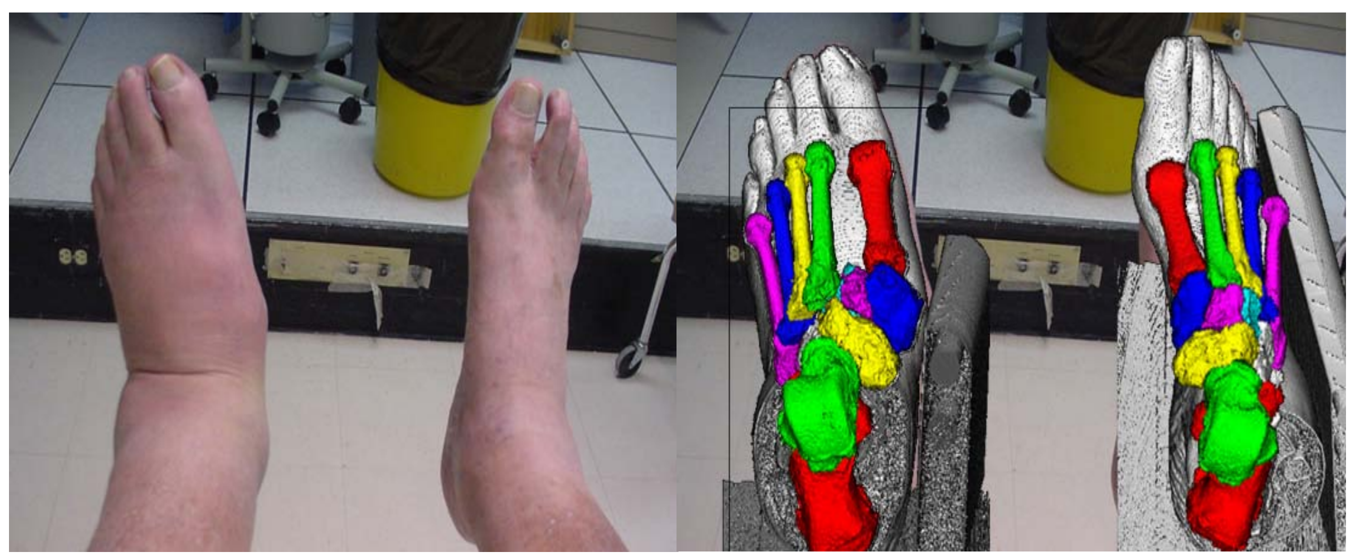
ABSTRACT

Charcot Neuroarthropathy (CN) is the leading cause of diabetes-related adult-acquired neuropathic foot deformities (200,000+ incident foot ulcers and 80,000+ amputations annually). Inflammation-accelerated loss of bone mineral density (BMD) leads to rapid, severe destruction of foot architecture. Improved methods are needed to detect and monitor regional inflammatory BMD loss in the foot.

We have developed a semi-automated quantitative CT image and atlas-based method for quantifying whole-bone and sub-regional volumetric BMD in the CN foot. A calibration is used to convert intensity to known values of BMD. 3D bone atlases are registered to bones segmented from the image data. Each bone atlas can be elastically registered within a common coordinate frame for direct visualization of sub-regional or whole-bone 3D BMD distributions over time and between subjects.

CHARCOT NEUROARTHROPATHY

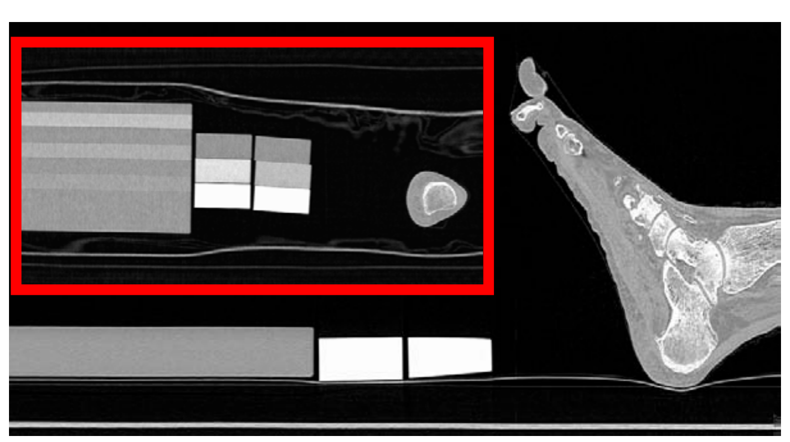
CN is characterized by rapid and severe bone and joint destruction resulting in fixed foot deformities, persistent skin ulceration, permanent disability and often lower extremity amputation. CN can be difficult for untrained medical professionals to diagnose as there are no diagnostic tests beyond radiographic changes evident only in well-established disease. Misdiagnosis, delayed recognition or inappropriate treatment interventions typically lead to poor outcomes as well as higher than expected mortality.



BONE MINERAL DENSITY CALIBRATION

Accurate determination of BMD from CT image data requires a mapping from measured intensity to known concentrations of Ca Hydroxyapatite

BMD precision is affected by kVp, table height, reconstruction kernel, etc. To control for these variables a calibration phantom is placed in the scan volume during each imaging session.



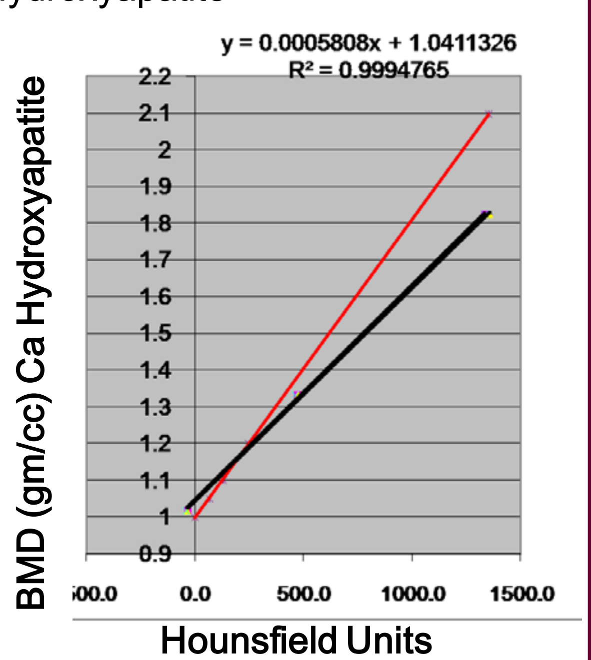
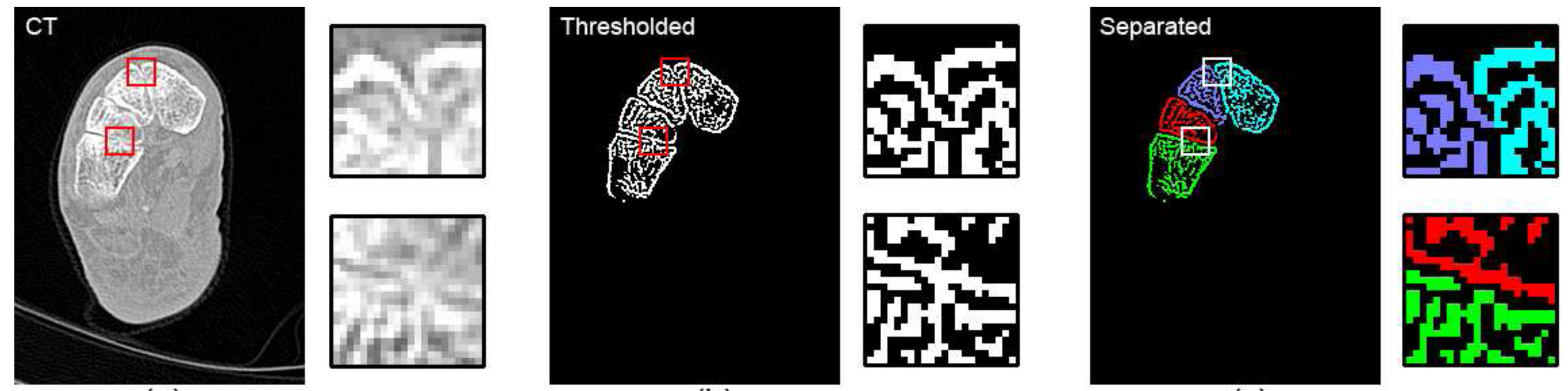


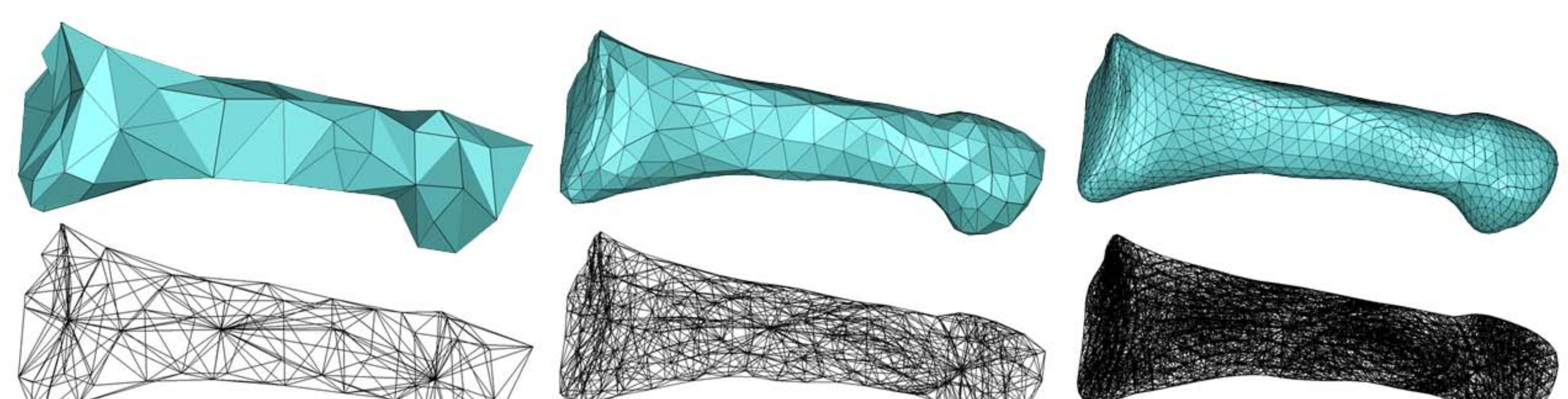
IMAGE SEGMENTATION



(a) (b) (c)

Individual bones are segmented from the CT volume in three steps. First, a threshold edge-detection filter is applied to obtain a binary volume (b) that contains only high density regions. Next, individual bones are separated from the binary volume (c). This is performed using a novel user interface where the user only needs to place a small number of seed points instead of going through all transverse slices. In our experiment, we found the use of the interface reduces the time needed for separating 12 mid-foot bones in a CT volume from 2.4 hours to 18 minutes with a maximum error of no more than 1.5%, Finally, each separated bone is filled in another interactive tool similar to Analyze to obtain a solid bone mask with an exterior surface.

ATLAS CONSTRUCTION



(A) (B) (C)

Each bone atlas is represented as a *tetrahedral subdivision mesh*. Subdivision is a fractal-like process that models a smooth shape by iterative refinement of an initial, coarse shape. Figure (A) show an example atlas of a second metatarsal modeled as a tetrahedral mesh (the interior mesh edges are shown at the bottom). This mesh is constructed by simplifying a segmented bone surface and tetrahedralizing the interior. Applying subdivision rules, this coarse atlas is refined in successive subdivision levels into smaller tetrahedral and octahedral elements with a smoother appearance. Figures (B) and (C) show results after one and two rounds of subdivision.

ATLAS REGISTRATION

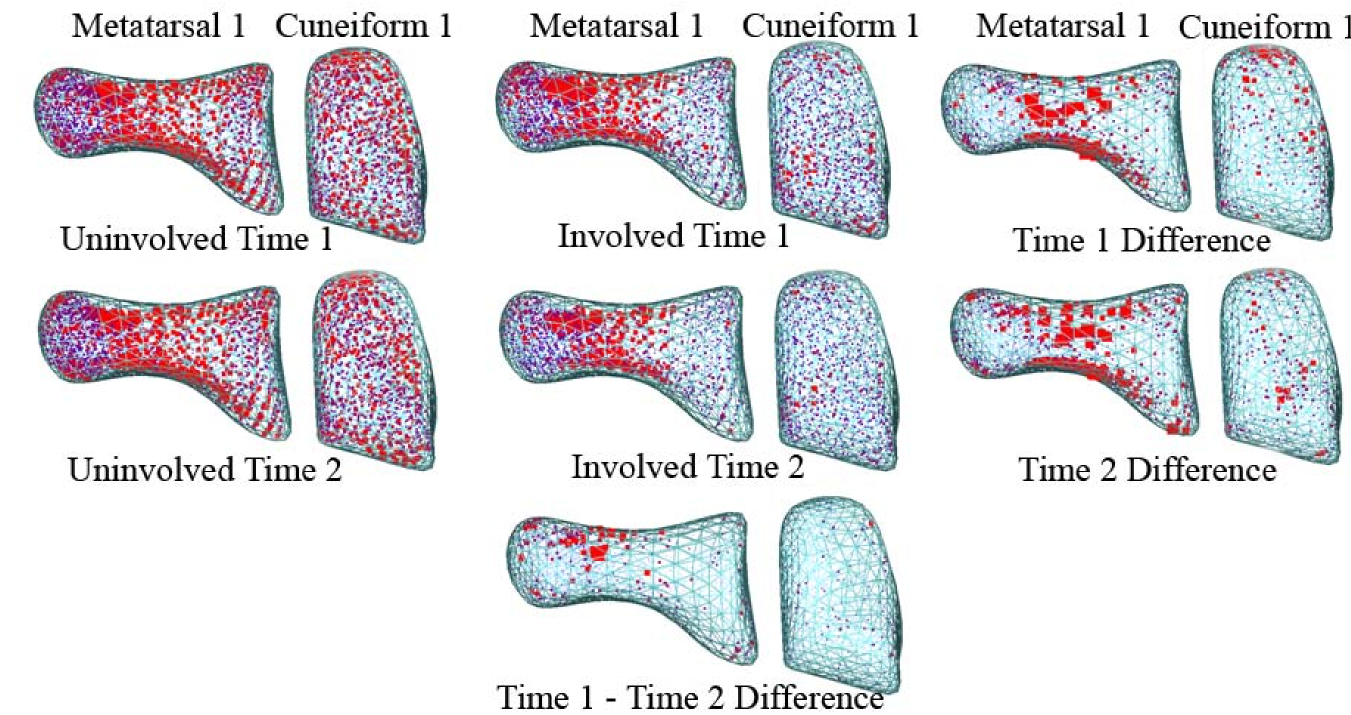
Given a segmented bone surface, the subdivision atlas is registered onto the surface by minimizing the following metric: (1)

$$E^k = E_f^k + E_d^k$$

Here, the first term measures the distance between the exterior vertices of the subdivision mesh (at level k) to the bone surface, and the second term measures the distortions of the shape of the interior tetrahedra, expressed as the amount of non-affine transformation of each tetrahedron from its original shape in the un-registered atlas.

Subdivision mesh is particularly suited for solving such registration problems, since a vertex at any subdivision level can be expressed as a linear combination of the (few) vertices in the coarse level. Hence minimizing (1) reduces to a least-square optimization problem that can be easily solved.

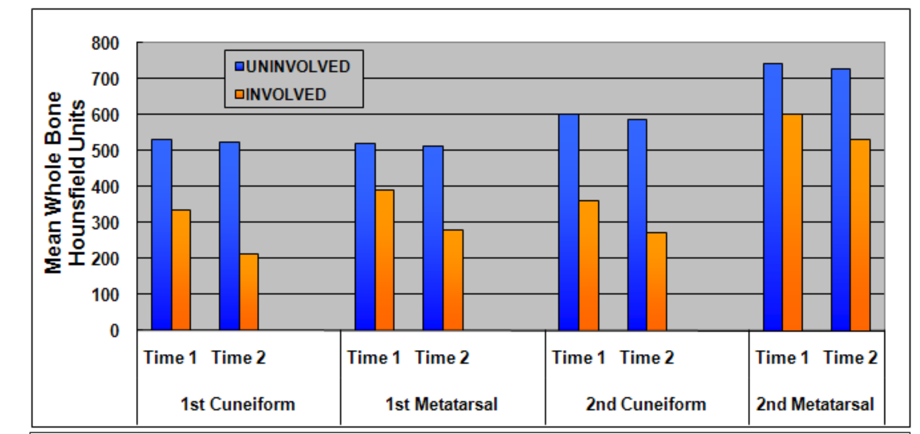
ATLAS-BASED BONE DENSITY ANALYSIS AND VISUALIZATION

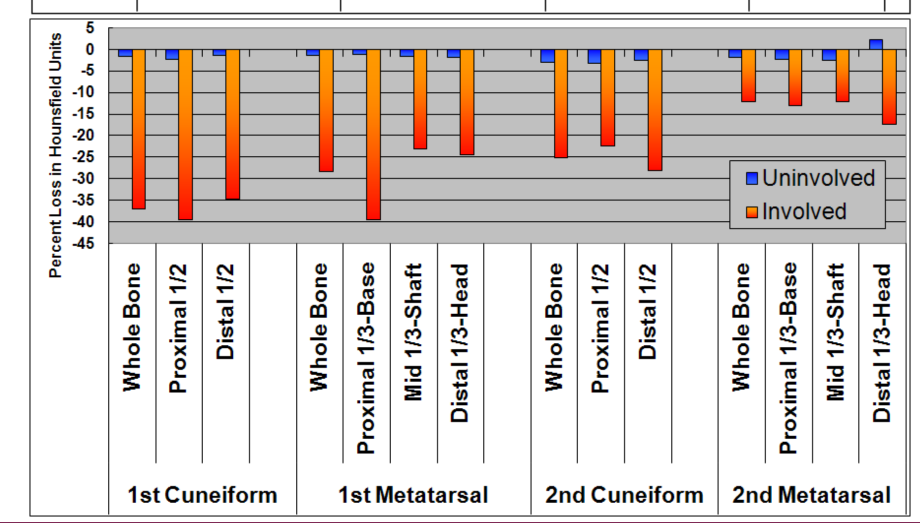


The above atlas images depict BMD changes shown over 3 months time and between the Uninvolved foot and the Involved foot.

The Uninvolved foot represents the BMD that should be achievable.

In this case the BMD is decreasing in the Involved foot indicative of a poor outcome. The top graph shows the mean whole bone Density in Hounsfield Units . The bottom graph shows percent change in sub-regions of the bone atlas.





CONCLUSIONS

Cuneiform1 and Met1 BMD decreased 37% & 28%, respectively over 3mos in a male subject with acute Lisfranc CN, while 2nd cuneiform and 2nd Met decreased 25% & 28%, respectively resulting in fixed foot deformity which places the subject at high-risk for ulceration.

Atlas-based imaging of all bones and important sub-regions of affected foot bones provide precise methods of detecting and monitoring inflammation-mediated BMD loss in CN progression.

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