Subject Specific Modeling of the Forefoot Based on CT 3D Reconstruction

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Introduction: Developing new surgical procedures and prototyping implants requires a real or adequate virtual testing environment to work in. Due to the unique architecture of the human foot interventions and implants can be tested only on patients and cadavers. We present our own approach for creating the geometrical model based on 3D CT reconstruction.

Material and methods: For the model construction we used the CT data from the foot of a healthy, young patient. The input data consisted from 56 sections from the talar dome to the plantar surface. The slices were segmented, boundary detection was performed, the boundaries were smoothed, NURBS interpolation was performed to obtain 3D surface. The surfaces were closed to solids and the solids edited to obtain the virtual anatomical structures.

Results: Our model is geometrically accurate in the limits of resolution that were given by the CT examination.

Conclusions: Now that we have an available model construction method we can begin enclosing the geometrical model into mathematical environments for finite element analysis. Also, scanning and reconstructing multiple feet with different conditions will help us to understand illnesses and develop new operative techniques and implants.

Keywords: forefoot, 3D reconstruction, CAD design

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Introduction

Pain free healthy feet are a key to a person's independence. Many foot problems don't respond to conservative treatment, surgical treatment is required. More than 130 operations have been described only for the treatment of hallux valgus. Diagnosing the problems and determining which technique to use can be difficult. Treatment which is poorly planned or executed leads to high levels of patient dissatisfaction [1]. Anatomically, the foot is a complicated structure with many joints and movements. The foot contains 26 bones, 33 joints, 107 ligaments and 19 muscles [2].

Developing new surgical procedures and prototyping implants requires a real or adequate virtual testing environment to work in. Due to the unique architecture of the human foot interventions and implants can be tested only on patients and cadavers. With the developing of computers and 3D modeling techniques several more or less adequate forefoot models have been developed. The first step for creating such a model is to define and replicate the geometrical conditions. We would like to present our own approach for creating the geometrical model based on 3D CT reconstruction.

Material and method

For the model construction we used the CT data from the foot of a healthy, young patient. The input data consisted from 56 sections from the talar dome to the plantar surface. The sections were taken at 3 mm distance in the Z plan. The planar resolution was 0.796875 x 0.796875 mm/pixel with 8 bit color depth (256 gray scale).

The first step was the selection of the slices which we have done with the help of MicroDicom software.

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The selected images were opened in ImageJ freeware image processing software written in Java (present work uses ImageJ 1.44p together with Java 1.6.0_20) [3,4].

With the formula $I = (I_0-250)/2$ we have eliminated the image intensities under the values of bone tissue intensities. In this formula I is the final intensity and I_0 is the original intensity of the pixel.

With Canny edge detector algorithm we had identified the contours of the different objects, then eliminated those that were outside the studied area (opposite foot) and saved the contours in a binary file.

We have superimposed the binary contours on the original CT images using our own software, manually corrected and closed them to boundaries. We used separate names and color for each bone, and marked the cortical and the cancellous layers (Figure 1). The boundaries were exported into binary files grouped by objects.

The boundaries where smoothed with an algorithm $C_{x,y} = 0.25*C_{x-1,y-1} + C_{x,y} + 0.25*C_{x+1,y+1}$ where $C_{x,y}$ are the coordinates of boundary points. NURBS interpolation was conducted on the boundary points, the resulting NURBS were simplified (Figure 2). A NURBS surface was generated on the closed contour curves (Figure 3). The surface was edited with the help of Autodesk Inventor 2009 then closed to a solid (Figure 4). Solids were intersected and combined to obtain the cortical, trabecular bone and the hollow medullary canal [5]. Every articular distance was measured divided by 2 and the articular surface was thickened by the resulting distance to obtain the articular cartilage (Figure 5). Ligaments and muscles were edited as simple bands based on the anatomical data.

The above described process was repeated but this time the segmentation threshold was set for tissue level intensity to obtain the skin surface.

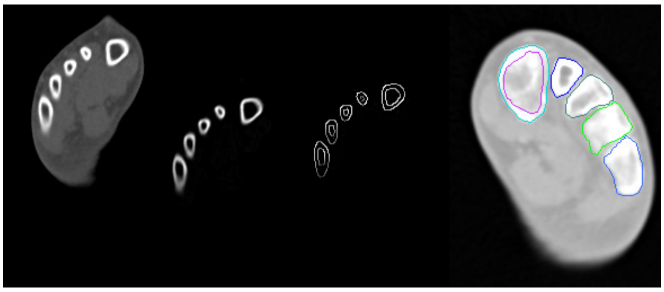

Fig. 1. From CT to boundary

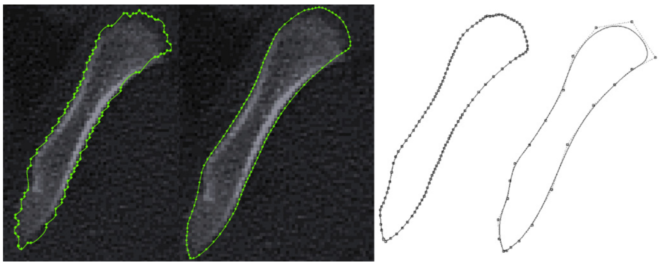

Fig. 2. Smoothing and simplifying algorithms

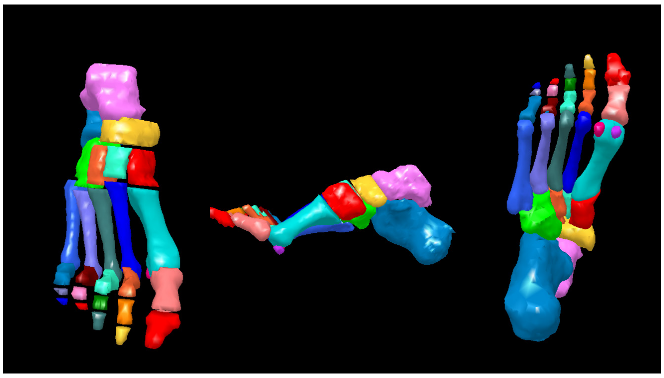

Fig. 3. Primary bone surfaces

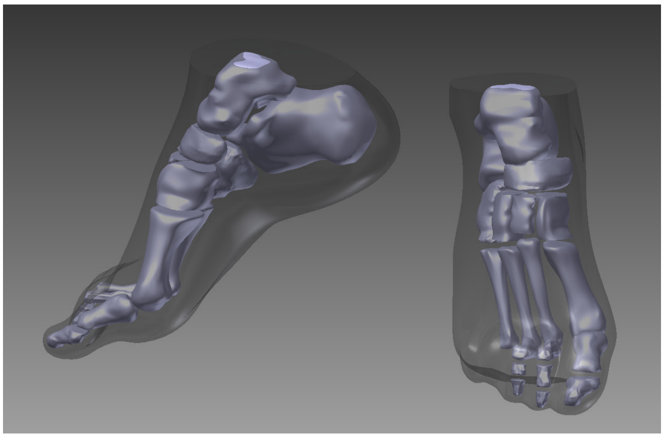

Fig. 4. Cleaned up solids with soft tissue

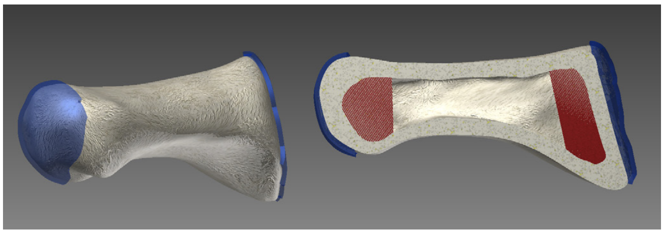

Fig. 5. Final model of the M1 metatarsal

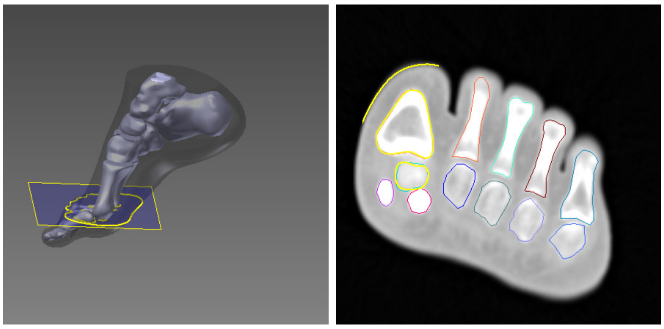

Fig. 6. Virtual CT slice at 133 mm, yellow is resulted boundary

Results

Our model is geometrically accurate in the limits of resolution that were given by the CT examination. Creating a model usually takes 40 work hours which – considering the fact that we have to model 26 bones + cartilage and soft tissue – in our opinion is fast. Our designed algorithms for boundary detection and smoothing as well for 3D surface interpolation performed well. For testing the accuracy of the model we have performed a virtual "CT scan" – we've sliced the model in several places according to the real CT scan superimposed the images and we were satisfied with the results (Figure 6). We hope that our method for generating cartilage will prove right during the finite element analysis. We have built a model that we believe is suitable for studying forefoot conditions.

Discussion

Using NURBS for surface reconstruction is not yet widespread in the medical modeling although in civil engineering it is [6]. We think that a good model should be scalable and the curvature should be accurate. The algorithms used on big bones cannot be successfully applied to small bones therefore higher accuracy and low levels of smoothing algorithms are required. Some errors and imperfections occur in the boundary detections due to resolution problems in manual mode and detection algorithms in automatic mode [7]. The geometrical accuracy of our modeled bones is though sufficient for mechanical modeling; we consider it superior than the models used in the literature [8,9]. Because its radio transparent cartilage is not visible on the CT scan, micro CT or MRI would be mandatory to obtain cartilage data [10]. However the thickening the articular surface – and not filling the gap between bones we think will create an optimal replacement for articular cartilage for finite element analysis. A fault of the model found also in the literature is the lack of infrastructure for performing CT examination for loaded foot [11]. Even in 2D plain radiographic examination of the foot the base rule is always perform it unloaded and loaded. Some authors are experimenting with acrylic plates and slings [12] we also considered using a radio-transparent well worked shoe of the patient. Making our model ready for mechanical analysis, defining the right boundary conditions and validating the mathematical model will be a serious challenge considering the number of geometrical bodies but based on literature data our model should behave well [13,14].

Conclusions

The methodology presented in this paper lays the foundation for further research. Our goal was the development of a virtual testing environment for simulation and static-mechanical testing of different treatment methods of various diseases of the forefoot – hallux valgus, claw toes, flatfoot and more. For that we have developed an available and reliable geometrical model construction method based on practically any type of planar sectional data (CT, MRI). The resulted geometrical model can be edited easily to correct or produce various forefoot deformities, simulate osteotomies and osteosyntheses. The edited geometrical models can be enclosed into mathematical environments for static or/and dynamic finite element analysis. We believe that scanning and reconstructing a large number of feet with different conditions (mandatory diagnostic examination) will help us to understand illnesses and develop new operative techniques and implants.

References

1. Robinson AHN, Limbers JP. Modern concepts in the treatment of hallux valgus. J Bone Joint Surg [Br]. 2005;87-B:1038-1045.
2. Tian-Xia Qiu, Ee-Chon Teo, Ya-Bo Yan, Wei Lei. Finite element modeling of a 3D coupled foot–boot model. Medical Engineering & Physics. 2011; 33:1228-1233.
3. Abramoff MD, Magelhaes PJ, Ram SJ. Image Processing. With Image J. Biophotonics International. 2004;11(7):36-42.
4. Kirana Kumara P, Ashitava Ghosal. A Procedure for the 3D Reconstruction of Biological Organs from 2D Image Sequences. 2011; http://eprints.iisc.ernet.in/id/eprint/38260.
5. Lijun Wu, Shizhen Zhong, Rongmei Zheng, et al. Clinical significance of musculoskeletal finite element model of the second and the fifth foot ray with metatarsal cavities and calcaneal sinus. Surg Radiol Anat. 2007;29(7):561-7.
6. Olya Grove, Khairan Rajab, Les A, et al. From CT to NURBS: Contour Fitting with B-spline Curves. Computer-Aided Design & Applications. 2011;8(1):3-21.
7. Arangio GA, Ciao D, Salathe EP. Biomechanical study of stress in the fifth metatarsal. Clinical Biomechanics. 1997;12(3):160-164.
8. Yu J, Tak-Man Cheung J, Fan Y, et al. Development of a finite element model of female foot for high-heeled shoe design. Clinical Biomechanics, 2008; 23:S31-S38.
9. Garcıa-Gonzalez A, Bayod J, Prados-Frutos JC, et al. Finite-element simulation of flexor digitorum longus or flexor digitorum brevis tendon transfer for the treatment of claw toe deformity. Journal of Biomechanics. 2009; 42:1697-1704.
10. Piscaer TM, Waarsing JH, Kops N, et al. In vivo imaging of cartilage degeneration using mCT-arthrography. Osteoarthritis and Cartilage. 2008; 16:1011-1017.
11. Camacho DA, Ledoux WR, Rohr ES, et al. A three dimensional, anatomically detailed foot model: A foundation for a finite element simulation and means of quantifying foot-bone position. Journal of rehabilitation Research and Development, 2002; 39(3):401-410.
12. Clark RA, Andrew Franklyn-Miller A, Falvey E, et al. Assessment of mechanical strain in the intact plantar fascia. The Foot. 2009;19:161-164.
13. Tak-Man Cheung J, Nigg BM. Clinical Applications of Computational Simulation of Foot and Ankle. Sportorthopadie Sporttraumatologie. 2007;23:264-271.
14. Matzaroglou C, Bougas P, Panagiotopoulos E, et al. Ninety-Degree Chevron Osteotomy for Correction of Hallux Valgus Deformity: Clinical Data and Finite Element Analysis. The Open Orthopaedics Journal. 2010; 4:152-156.