dimensions.

Methods

The model developed in Matlab combines the principle of the classical RBSM and the *sliding* spring approach introduced by Manal [7]. The cartilage surface is modeled with a row of springs acting only in compression and the ligaments are modeled with springs acting only in tension. The model uses a 4th order Runge-Kutta integration formula to integrate the reaction forces and determine the relative body displacements. In order for the model to handle the high relative rotations of the ankle, a function was incorporated in the model to allow the sliding of the springs. This function analyzes each spring attached to the body. It detaches the spring from the body and attaches it again at a shorter distance. To calculate this distance, the function looks at the four equidistant points to the left and right of where the spring was detached. The point giving the shortest distance will be the new point of attachment. This method comes from the assumption that the relative movement between the bodies at each time step will be less than the distance from the current point to the fourth equidistant point [7]. The model calls this function at every interval of motion integration. Before applying the model throughout the whole ankle structure, its efficacy was tested on the sample geometry seen in figure 1 which represents the morphology of the talocrural joint (ankle

Introduction

The ankle structure is among the most complex structures of the human body. It is comprised of seven tarsal bones, the tibia, and the fibula. This structure along with the rest of the foot serves the purpose of weight bearing and also shock absorbing. It is essential to accurately calculate the contact forces in the articular joints of the ankle not only to determine contact stresses but also for joint stability. Due to the repeated loading of these joints, dynamic analysis becomes necessary in determining their contact forces. Once these values are defined, joint function and interaction during gait can be better understood. To determine the contact forces and contact stresses at joint surfaces, accurate dynamic modeling is required. Many have attempted to model the interactions of articular joint by methods of finite element analysis (FEA) or the rigid body spring model (RBSM). Finite element analysis has become more and more popular with the increase in computer technology but it still offers the limitation of only being able to handle static systems. Some such as Gefen [1] have done quasistatic analysis of the ankle and foot structure using the finite element method and have shown stress concentrations at the different stances of gait. In general, the limitation of quasistatic studies is that the dynamic effects of repetition are not simulated and therefore not taken into consideration. The RBSM first introduced in a civil engineering problem by Kawai [2] has been used several times by authors to simplify problems pertaining to articular joints [3]. It consists of rigid bodies connected by a series of compressive springs representing soft tissue. FEA and RBSM have proven to be useful in modeling articular joints but neither can capture time dependant interactions of the articulating joints of the ankle during gait [4-7]. In average there is a 27.9° rotation along the Transverse axis (along the Sagittal plane) between the talus and tibia when taking the foot from 30° plantar flexion to its neutral position [4]. As discussed by Manal [7], these high rotations cause problems when modeling cartilage using the RBSM. In the RBSM, cartilage is modeled with compressive loads represented by springs that work only in compression and not in tension. When the bodies are exposed to high relative rotations, some of the compressive springs may elongate and

fail when in all actuality the cartilage at that spot is active and applying resistance. Manal proposed a *sliding* RBSM where the springs are permanently attached to one body and the other end is allowed to slide along the adjacent body. This avoids the collapse of the model. In order to accurately model the interaction of articular joints that are exposed to high relative rotations, the present study presents a novel approach to both the classic RBSM and the *sliding* RBSM. In the model presented, the springs representing the cartilage will be changed to spring and damper units attached in parallel to better represent viscoelastic properties, springs will be allowed to slide along the surface of the bones when high relative rotations occur, and varying values for the stiffness of the springs will be incorporated to better represent the three dimensional properties of cartilage in two

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joint). Here the round body is attached to the bottom body by seven compressive springs representing cartilage and two tensile springs representing ligaments. To first test the model, the round body was loaded in the vertical direction and allowed to come to equilibrium. The same configuration was setup using a RBSM. Both models were allowed to run for 0.05 seconds at a time step of 5E-6.



Figure 1. Sample Geometry

The sample geometry was also tested with a moment applied to the circular body. Finally, correct morphology from the ankle structure was loaded into the model. Bone geometries and cartilage thickness were collected from digitized MRI scans along the Sagittal plane of the foot. The Young's modulus and Poisson's ratio for bone and soft tissue were taken from previous experimental studies [8-10].

<u>Results</u>

The results from the sample model can be seen in figure 2 and 3.



Figure 3. NDBRSM with Sliding Springs

As seen from figure 2, the RBSM model showed to be highly unstable with the geometric setup and loading conditions. The compressive springs failed and couldn't accurately represent the articular cartilage leading to the collapse of the model. It can be seen in figure 3 that the model developed converged under the same geometric setup and loading conditions. As can be seen in figure 4, the model converged and the top body reached equilibrium (x, y, F). When the moment was applied, the springs in the model allowed the circle to rotate. When applied to the entire ankle structure, the model also converged.



Figure 4. Position (mm) vs. Time (s)

Conclusions

During this study, a model was devised for use in representing articular joints that are submitted to high relative rotations. Although the model is computationally more costly it is ultimately necessary for more accurate representation of the dynamics of the joint system. Ultimately this model will be used for a comparative evaluation of different surgical procedures pertaining to Flexible Flatfoot.

References

- Gefen, A., Medido-Ravid, M., Itzchak, Y., and Arcan, M., 2000, "Biomechanical Analysis of the Three-Dimensional Foot Structure During Gait: A Basic Tool for Clinical Applications," J. Biomechanical Engineering, 122, pp. 630-639.
- Kawai, T. and Takeuchi, N. 1981, "A Discrete Model of Limit Analysis with Simplified Elements," ASCE Proc. Int. Conf. On Computing in Civil Engineering. New York, May 12-14, pp.1-16.
- Li, G., Sakamoto, M., and Chao, E. Y. S., 1997, "A Comparison of Different Methods in Predicting Static Pressure Distribution in Articular Joints," J. Biomechanics. 30, pp. 625-638.
- Lundberg, A., Goldie, I., Kalin, B., and Selvik, G., 1989, "Kinematics of the Ankle/Foot Complex: Plantarflexion and Dorsiflexion," Foot & Ankle, Vol. 9, No. 4, pp. 194-200.
- 5. Seireg, A., and Arvikar, R. J., 1975, "The Prediction of Muscular Load Sharing and Joint Forces in the Lower Extremities During Walking, "J. Biomech., 8, pp. 89-102.
- Rohrle, H., Scholten, R., Sigolloto, C., and Sollbach, W., 1984, "Joint Forces in the Human Pelvis-Leg Skeleton During Walking," J. Biomech., 17, pp. 409-424.
- Manal, K., Lu, X., Nieuwenhuis, M., Helders, P., and Buchanan, T., 2002, "Force Transmission through the Juvenile Idiopathic Arthritic Wrist: a Novel Approach Using a Sliding Rigid Body Spring Model," J. Biomechanics, 35, pp. 125-133.
- Athanasiou, K. A. Liu, G. T., Lavery, L. A., Lanctot, D. R., and Shenck, R. C., 1998, "Biomechanical Topography of Human Articular Cartilage in the First Metatarsophalangeal Joint," Clin. Orthop., 348, pp. 269-281.
- Liu, G. T., Lavery, L. A. Shenck, R. C., Lanctor, D. R., Zhu, C. F., and Athansiou, K. A. 1997, "Human Articular Cartilage Biomechanics of the Second Metatarsal Intermediate Cuneiform Joint," J. Foot Ankle Surg., 36, pp. 367-374.
- Nakamura, S., Cronwninshield, R. D. and Cooper, R. R., 1981, "An Analysis of Soft Tissue Loading in the Foot: A Preliminary Report," Bull. Prosthet. Res., 18, pp. 27-34.