INTRODUCTION

Joint instability has been implicated closely in development of osteoarthritis. Abnormality in joint kinematics is thought to involve injurious-level cartilage contact stress aberrations, although the pathomechanical details are still unclear. In this study, a human ankle cadaver model was utilized to create various levels of instability, and associated changes in dynamic articular contact mechanics were quantified. The purpose was to identify the correlation of dynamic contact stress aberrations with severity of joint instability.

METHODS

To model joint instability, potentially unstable cadaver ankles were created by impairing passive restraints. To reduce articular surface restraint, a step-off incongruity was created on the distal tibial surface. A full-width coronal osteotomy was made at the anterior one-third of the distal tibia (Fig. 1A), and the osteotomized fragment was rigidly secured in a proximally-displaced position (Fig. 1B). Ligamentous restraint was reduced by transecting the anterior talo-fibular ligament. With these alterations, a posteriorly directed force to the tibia was expected to sublaxate the talus anteriorly under the tibia (Fig. 1C).

Figure 1: Modeling concept

Six cadaver specimens were subjected to a loading experiment, in which a custom fixture mounted in an MTS machine applied simulated stance-phase ankle motion at a rate of 0.5 Hz, under a compressive load held at 300N. The A/P tibial loading protocol consisted of a constant anteriorly directed “baseline” force (30N, for initial stabilization) and a superimposed posteriorly directed force pulse (for subluxating the ankle transiently, in some cases). The force pulse was applied at 45 to 70 % of cycle time, and the peak magnitude ranged from 0 to 120 N in 20 N increments.

Each specimen was first tested intact. After a baseline test (with no force pulse), tests were repeated while varying pulse magnitude randomly. After tibial osteotomy, tests were repeated with the tibial surface reduced anatomically and with 1mm and 2mm step-off conditions, both before and after ligament transection. A/P tibial displacement during testing was measured; the data were utilized to quantify abnormality of joint kinematics.

Ankle contact stresses were measured by a thin and flexible TekScan® sensor inserted into the joint. The sensor measured instantaneous contact stresses at 1472 sites (32 by 46 array), at a sampling rate of 132 Hz. Data from the 40 to 90 % cycle-time were analyzed. To evaluate changes in dynamic contact stress mechanics, the rates of change of contact stress were computed using a Lagrange four-point central differencing formula (positive/negative values indicate instantaneously increasing/decreasing cartilage contact stress, respectively).
RESULTS

In every specimen, visually distinct instability events occurred when a step-off incongruity was introduced, with pulse load magnitudes beyond a threshold specific to each specimen/condition (range, 20 to 100 N). Peak tibial displacement data (Fig. 2) revealed that instability occurred primarily due to step-off incongruity, and more severe instability occurred with the higher step-off. Instability was enhanced by ligament transection, although ligament transection alone did not lead to detectable change. (One-way ANOVA, significance-level p = 0.05.)

The effect of instability on dynamic cartilage contact mechanics was characterized by elevated rates of contact stress change, as evidenced by the expanded width of the 95% distribution range of the rate data (absolute difference between positive and negative 95th percentile values). Gathering the data across test series in each specimen (which yielded a wide spectrum of instability situations), this measure was found to be correlated linearly with the severity of instability (R² ranged from 0.79 to 0.97, averaging 0.92) (Fig. 3).

CONCLUSIONS

In this study, abnormal tibial surface geometry caused unstable ankle motion during dynamic loading, and its severity was dependent on the level of abnormality. It is suggested that altered joint geometry after mal-reduced distal tibial intraarticular fracture can cause joint instability, supporting the clinical belief that anatomical fracture reduction is essential for minimizing biomechanical residuals after intraarticular fractures. Parametric analysis with a contact FE model would allow identifying an acceptable form/range of geometric abnormality, and patient-specific modeling would also be helpful for planning effective reduction/reconstruction surgeries.

The rates of contact stress change were correlated linearly with the severity of joint instability. In experimental settings, evaluation of dynamic cartilage contact stress aberrations appears to be reasonable means to explore the small, fast abnormal joint motions that involve contact stress aberrations potentially injurious to cartilage. For example, application of this paradigm to a human cadaver knee experiment would allow study of potential pathomechanisms of osteoarthritis secondary to ACL injury.

ACKNOWLEDGEMENTS

CDC Grant R49 CCR721745
NIH Grant 5 P50 AR048939