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Development of a statistical shape model of the patellofemoral joint for investigating relationships between shape and function

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ABSTRACT

Patellofemoral (PF)-related pathologies, including joint laxity, patellar maltracking, cartilage degradation and anterior knee pain, affect nearly 25% of the population. Researchers have investigated the influence of articular geometry on kinematics and contact mechanics in order to gain insight into the etiology of these conditions. The purpose of the current study was to create a three-dimensional statistical shape model of the PF joint and to characterize relationships between PF shape and function (kinematics and contact mechanics). A statistical shape model of the patellar and femoral articular surfaces and their relative alignment was developed from magnetic resonance images. Using 15 shape parameters, the model characterized 97% of the variation in the training set. The first three shape modes primarily described variation in size, patella alta–baja and depth of the sulcus groove. A previously verified finite element model was used to predict kinematics and contact mechanics for each subject. Combining the shape and joint mechanics data, a statistical shape–function model was developed that established quantitative relations of how changes in the shape of the PF joint influence mechanics. The predictive capability of the shape–function model was evaluated by comparing statistical model and finite element predictions, resulting in kinematic root mean square errors of less than 3° and 2.5 mm. The key results of the study are dually in the implementation of a novel approach linking statistical shape and finite element models and the relationships elucidated between PF articular geometry and mechanics.

1. Introduction

Patellofemoral (PF)-related pathologies in the natural knee, including joint laxity, patellar maltracking, cartilage degradation and anterior knee pain, affect nearly 25% of the population (Cleland and McRae, 2002; Naslund et al., 2006), while complications related to the PF joint remain a common cause for revision of total knee replacements (TKR) (Dalury and Dennis, 2003; Fehring et al., 2001; Boyd et al., 1993). Various factors, including articular geometry, passive soft-tissue constraint and muscle loading, affect the mechanics of the joint, with articular geometry reported as a major determinant of patellar tracking (Varadarajan et al., 2010; Amis et al., 2008; Heegaard et al., 1994). Understanding the influence of articular geometry on kinematics and contact mechanics can provide valuable insight into the mechanisms of injury of the PF joint. Patellofemoral pain, for instance, has been related to abnormal PF kinematics; it has been hypothesized that maltracking of the patella may reduce contact area and increase joint contact stresses and cartilage degeneration (Fulkerson and Shea, 1990).

Prior studies have investigated the shape of the PF joint and assessed its contribution towards joint laxity and mechanics. Connolly et al. (2009) used MR images to estimate PF contact area in normal subjects and PF pain patients at low flexion angles (up to 45°). Luyckx et al. (2009) assessed relative alignment (specifically patella alta) on PF contact mechanics using a pressure sensitive film on cadaveric specimens in a dynamic knee simulator. Innocenti et al. (2011) carried out a design-of-experiments (DOE) style analysis (varying patella alta/baja position and internal–external (I–E) rotation, as well as tibial parameters) in four different implanted geometries, determining that PF contact forces were primarily affected by patellar height. Several studies have investigated correlations between PF kinematics and patellar or femoral shape measures in the natural knee (Harbaugh et al., 2010; Sheehan et al., 2009; Jafari et al., 2008; Powers, 2000). Heinert et al. (2011) compared patellar tracking between natural

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