INTRODUCTION

Collagen fibers in the annulus fibrosus (AF) play a significant role in maintaining the disc mechanical behavior. In healthy discs, AF fibers are concentrically arranged in a zigzag fashion. Tensile loads are transmitted to these fibers when the disc is loaded in compression. As a result, disc bulging occurs. Initiation and progression of mild cervical disc degeneration (DD) has been the subject of clinical concern [1]. The mild DD is associated with structural interruption in laminar organization of fibers in partial AF regions and incomplete length of fibers is a major form of structural interruption in AF fibers [2]. Moreover, a loss of lamellar fiber structure contributes to the progression of spinal deformity [3]. Past research have documented the biomechanical role of complete length of fibers in governing a healthy disc behavior [4]; however, there is a lack of clear understanding as to how incomplete length of fibers in different AF regions affect overall disc biomechanics and how they may play a role in initiating the propagation of DD. The focus of the current study is to investigate the disc biomechanical response due to incomplete length of fibers in outer, middle, and inner AF regions.

MATERIALS AND METHODS

A previously validated three-dimensional finite element (FE) model of a C5-C6 motion segment (without posterior elements) was used [5]. The spinal structures included cortical bone, cancellous bone, endplates, AF, and nucleus pulposus (NP). The C5-C6 motion segment was chosen for the analysis because this segment is the cervical segment most susceptible to DD [6]. The AF anisotropy was simulated by modeling six layers of collagen fibers oriented in a zigzag fashion at an angle of ±70° with respect to the horizontal plane. Four of these six fiber reinforced layers were embedded in the AF tissue matrix between outer AF and AF-NP boundaries, dividing the AF tissue matrix into five radial regions; and a fiber layer was simulated on each of the outer AF and AF-NP boundaries. Fiber layers varied radially from fiber layer I (outermost) to fiber layer VI (innermost). The volume of the AF tissue matrix was also radially subdivided into five regions based on AF volume between these fiber layers – region I (AF volume between fiber layers I and II), region II (AF volume between fiber layers II and III), region III (AF volume between fiber layers III and IV), region IV (AF volume between fiber layers IV and V), and region V (AF volume between fiber layers V and VI). The AF fibers ran from superior to the inferior disc surfaces along the frontal and sagittal planes, and were termed as “complete” in regards to their length. The model with complete (100%) length of AF fibers in a zigzag (X) fashion was referred as a model M100.

From model M100, three additional models were developed corresponding to incomplete length of fibers in three different AF regions – outer, middle, and inner AF regions; and these models were referred as M50-O, M50-M, and M50-I, respectively. The incomplete fibers ran only 50% of their length compared to the fibers length in model M100, and were simulated in a wedge (>) fashion originating from superior or inferior disc surfaces up to mid disc space [7]. Two additional models, M50-OM and M50-MI, were also built. M50-OM was simulated with incomplete lengths of fibers in the outer and middle AF regions, whereas these set of fibers in M50-MI were simulated in the middle and inner AF regions.

In these FE models, the C6 inferior surface was fixed in the three perpendicular planes and a compressive load equivalent to the upper body weight of 50 N was applied on the C5 superior surface. The dimensions of the spinal structures and their material properties were adopted from the literature. The compressive stresses in the five AF regions, von-Mises stresses in the six fiber layers, and disc bulging were recorded for the six FE models. The analysis was performed...
using commercial FE software, ABAQUS (Dassault Systemes Simulia Corp, Providence, Richmond, USA).

RESULTS

The compressive stresses (in MPa) were computed in the five AF regions (Figure 1). The AF compressive stresses in the models with incomplete length of fibers were higher than corresponding stresses in the model with complete length of fibers. Compared to regional AF stresses in model M100, the corresponding AF stresses in the models with incomplete length of fibers increased steadily from AF regions I (outermost) to V (innermost). With incomplete length of fibers varying radially inside the AF (from models M50-O to M50-M, and to M50-I) and higher in their numbers (models M50-OM and M50-MI), the AF tissue matrix was more stressed inside than the outside AF tissue matrix.

The von-Mises stresses (in MPa) were computed in the six AF fiber layers (Figure 2). Compared to model M100, the fiber von-Mises stresses decreased in the fibers with their incomplete length and increased in the fibers with their complete length. With increasing layers of incomplete length of fibers (models M50-OM and M50-MI), the stresses on complete length of fibers further increased. The disc bulging (in mm) was noted to be highest in the anterior AF region. It increased from model M100 (0.0212) to models M50-O (0.0249), M50-M (0.0266), M50-I (0.0273), M50-OM (0.0365), and M50-MI (0.0380).

DISCUSSION

The current study investigated disc biomechanics due to incomplete length of fibers in different regions of AF. Stresses in the inner AF regions increased when incomplete length of fibers ranged from outer to inner AF regions and when more layers of incomplete length of fibers were present in the AF. Such variations in stress patterns within AF tissue matrix together with increased disc bulging may initiate a cascade of disc degenerative disease events, in which early signs of DD are shown by degenerative changes in the inner disc regions [8]. Also disorganization in AF fibers and resulting fiber stresses may represent a mechanism for disc tear formation and tissue delamination, that can together lead to the initiation and progression of mild DD [9-10]. The limitations of the present study included the absence of posterior elements and modeling of only six fiber layers instead of 15-20 fiber layers. Future biomechanical in vitro experimental work including incomplete length of fibers may be needed to verify the current findings.

REFERENCES