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Effects of dividing the transverse carpal ligament on the mechanical behavior of the carpal bones under axial compressive load: A finite element study

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Abstract

Transecting the transverse carpal ligament (TCL) is a routine procedure to surgically treat carpal tunnel syndrome; yet, its mechanical consequences on carpal bones are unclear. In this study, our intent was to perform a computational analysis of carpal biomechanics resulting from TCL release. A three-dimensional finite element model of the wrist was constructed, which included all the carpal bones, the distal ulna and radius, the proximal metacarpals and the interosseous ligaments. Cartilage layers of each bone were modeled manually according to anatomic visualization software. The TCL was also modeled in three dimensions and added to the bone model. A 100-Newton axial load was applied to the upper section of the second and third metacarpals. The effects of dividing the TCL on the displacements of the carpal bones and the contact stress distribution in the midcarpal joints were studied using a finite element analysis method. When the TCL was divided, the axial compressive load resulted in the carpal bones deviating more radially. More specifically, the carpal bones on the radial side of the capitate and lunate (i.e. the trapezium, trapezoid, and scaphoid) moved further toward the radius, and the carpal bones on the ulnar side of the capitate and lunate (i.e. hamate, triquetrum, and pisiform) moved further toward the metacarpals. The contact stresses and contact locations in the midcarpal joints changed as a result of dividing the TCL. The changes in displacements of carpal bones and the contact stress distributions in the midcarpal joints due to TCL release may be implicated for some of the postoperative complications associated with carpal tunnel release.

Keywords: Carpal tunnel; Transverse carpal ligament; Contact stress; Three-dimensional finite element analysis

1. Introduction

Carpal tunnel syndrome is a common hand disorder, and is routinely treated by carpal tunnel release procedure to transect the transverse carpal ligament (TCL). Morphologic changes after carpal tunnel release have been studied using ultrasound, computer tomography and magnetic resonance imaging [1–4]. There have also been studies of the influence of dividing the TCL or some intercarpal ligaments on carpal stability [4,5]. To explore an alternative treatment method, lengthening of the TCL by sustained tensile loads [6] or using a transposition flap technique [7] has also been studied. For example, Sucher et al. reported increases in carpal arch width and carpal tunnel volume due to the release of the carpal tunnel.

However, the effects of dividing the TCL on the mechanical behavior of the carpal bones remain unclear. Patients after carpal tunnel release often experience postoperative complications such as scar sensitivity, pillar pain, recurrent symptoms, and grip weakness. It is suggested that these complications may be attributed to a change in the carpal articulation or changes in the flexor tendon pulley system [8]. Kinematically, an interruption of the proximal carpal row in the carpus results in carpal instability [9]. When the carpus is unstable, it is not able to bear loads and does not have normal kinematics during hand tasks.

Finite element (FE) analysis is a useful tool for studying musculoskeletal biomechanics. However, the FE modeling of the wrist has been challenging due to the material, structural,

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and mechanical complexity of the wrist. Previous FE analysis of the wrist was simplified to two-dimensional [10,11] due to the number of bodies involved and the complexity of the soft tissue interaction. The few three-dimensional finite element models simulated only a part of the wrist, such as the load transfer analysis model through the distal radius [12], which involved only the distal radius and the adjacent scaphoid and lunate. A study by Carrigan et al. [13] developed a three-dimensional finite element model including carpal bones and distal ulna and radius that modeled cartilage layers between the bone articulations by simply extruding cartilage elements from each bone surface. This arrangement made the surface of each bone bumpy and is not optimal for simulating truly mechanical behavior on the surface of bones. In this study, we established a three-dimensional finite element model of the wrist, which includes carpal tunnel (including carpal bones and the TCL), distal radius and ulna, proximal metacarpals, and related ligaments. All of the bones were modeled with cartilage layers smoothly embedded in them. With the model, we examined the effect of dividing the TCL on the displacement of the carpal bones and stress distribution at the carpal and radiocarpal joints.

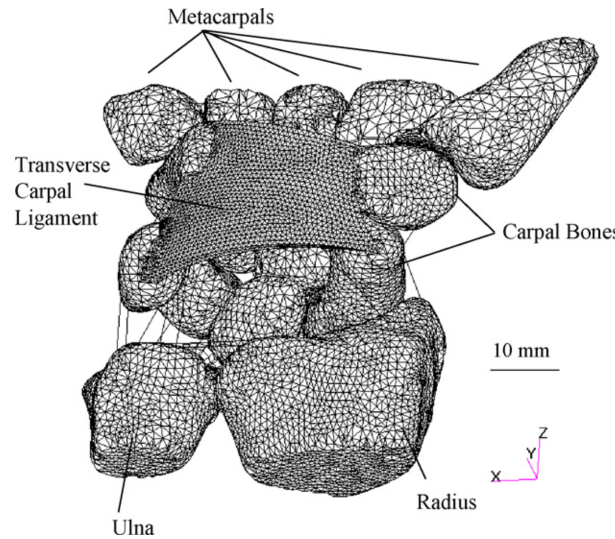

Fig. 1. Three-dimensionally meshed model of the wrist.

2. Method

The geometry of the computer model of the carpal bones was based on a three-dimensional reconstruction of computer tomography (CT) scan images (1 mm intervals) from a right wrist of a 24-year-old male healthy volunteer. The scanning images covered from the distal radius and ulna to the proximal portion of the metacarpals. These images were imported into the MIMICS (Materialise Corp, Leuven, Belgium) to reconstruct a three-dimensional surface meshed model of the bones. The surface meshes were then converted into solid meshes using MSC.PATRAN (MSC Software Corp., Detroit, USA).

Cartilage layers at the site of bony articulations were selected and recorded using the anatomic visualization software (Interactive Hand 2000, Primal Pictures Ltd., London, UK). By referring to previous study, the thickness of the cartilage was set to be 1.0 mm [14]. To construct the cartilage three-dimensionally and also maintain a smooth surface of each bone, both the cartilage layers selected and the surrounding bone layers were offset inwardly by 1.0 mm. Vector projection was then used to extrude these layers outwardly by 1.0 mm and build the surface solid cartilage elements and bone elements in the shape of wedges. Manual work was conducted to modulate elements and nodes in order to locally refine the edges of the cartilage elements and bone elements. The cartilage elements were then configured in MSC.Patran as contact elements.

The TCL was meshed as solid tetrahedral elements. This ligament was attached to the bony elements of the scaphoid tuberosity and ridge of the trapezium radially and the hamulus and pisiform ulnarly. Its thickness was set to be 1.5 mm in average [15]. Related ligaments of the wrist were modeled by referring to previous studies [13–16]. Each of these ligaments was modeled using two non-linear, tension-only spring elements by connecting the corresponding insertion sites, according to the anatomic visualization software (Interactive Hand 2000, Primal Pictures Ltd., London, UK). To prevent excessive rotation of unconstrained bones and improve computation convergence, each of these ligaments was specified to have a linear region below 5% strain in the force–length curves [13].

Assembly of the wrist and related structure was completed by combining the cartilage and ligament with the bony model (Fig. 1). The standard mesh size was set to be 1.0 mm, with different deviations in certain elements considering element shapes and qualities. All solid elements were specified to have linear elastic material properties. Cartilage elements were assumed to have a modulus of 10 MPa and a Poisson's ratio of 0.45 [17,18]. Bone elements were specified to have a modulus of 10,000 MPa and a Poisson's ratio of 0.3 [17]. The elastic modulus and Poisson's ratio of the TCL was assigned to be 300 MPa and 0.4, respectively [19]. The mechanical parameters of other ligaments were defined as non-linear springs by referring to previous literature [13]. For a strain under 5%, the stiffness of the ligaments was considered linear and their stiffness parameters were defined in a range from 40 to 350 N/mm based on previous study [16]. The strain beyond 5% was limited by increasing the specified linear stiffness by a factor of 10.

An anatomically detailed three-dimensional finite element model of the skeleton–ligament complex of the right wrist of a volunteer was developed, involving four tissues (bone, cartilage, TCL and other ligaments), 58,112 nodes and 239,935 elements (Table 1). All anatomic components of the model were shown in Fig. 1. Convergence tests were conducted using different mesh densities, and the results indicated that