



Finite element based estimation of contact areas and pressures of the human scaphoid in various functional positions of the hand

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ARTICLE INFO

Article history:

Accepted 30 November 2012

Keywords:

Wrist
Scaphoid
Biomechanics
Finite element method
HR-pQCT

ABSTRACT

The scaphoid is the most frequently fractured carpal bone. When investigating fixation stability, which may influence healing, knowledge of forces and moments acting on the scaphoid is essential. The aim of this study was to evaluate cartilage contact forces acting on the intact scaphoid in various functional wrist positions using finite element modeling. A novel methodology was utilized as an attempt to overcome some limitations of earlier studies, namely, relatively coarse imaging resolution to assess geometry, assumption of idealized cartilage thicknesses and neglected cartilage pre-stresses in the unloaded joint. Carpal bone positions and articular cartilage geometry were obtained independently by means of high resolution CT imaging and incorporated into finite element (FE) models of the human wrist in eight functional positions. Displacement driven FE analyses were used to resolve interpenetration of cartilage layers, and provided contact areas, forces and pressure distribution for the scaphoid bone. The results were in the range reported by previous studies. Novel findings of this study were: (i) cartilage thickness was found to be heterogeneous for each bone and vary considerably between carpal bones; (ii) this heterogeneity largely influenced the FE results and (iii) the forces acting on the scaphoid in the unloaded wrist were found to be significant. As major limitations, accuracy of the method was found to be relatively low, and the results could not be compared to independent experiments. The obtained results will be used in a following study to evaluate existing and recently developed screws used to fix scaphoid fractures.

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1. Introduction

The scaphoid is the most mobile and the most frequently fractured carpal bone (Berger, 2001; Hove, 1999; Tassel et al., 2010), injured mostly in young active individuals (Steinmann and Adams, 2006). Single screw osteosynthesis allows for early functional therapy, but fixation stability may influence the healing process and determine its outcome. This however can only be analyzed properly if the external forces acting on the bone are known. As a first step towards this, loading of the intact scaphoid should be determined.

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Experimental assessment of joint contact forces by means of analog or digital pressure sensitive films are limited to specific contact surfaces and usually restricted to *in vitro* conditions (Tang et al., 2009). *In vivo* investigation is also possible (Rikli et al., 2007) but invasive. Numerical modeling offers an alternative to determine both cartilage and ligament forces acting within the wrist joint. Rigid body spring modeling has been used to calculate load transmission and contact forces within the radiocarpal joint in one specific (Iwasaki et al., 1998; Majima et al., 2008) or more (Genda and Horii, 2000; Fischli et al., 2009) wrist positions. Towards similar aims, multi-body contact models (Kwak et al., 2000) used penetration-based estimation of contact forces without (Pillai et al., 2007) or with (Marai et al., 2009; Dvinskikh et al., 2011) ligaments. Recently, 2D (Ledoux et al., 2008) and 3D (Anderson et al., 2005; Carrigan et al., 2003; Troy and Grabiner, 2007; Guo et al., 2009; Gislason et al., 2010) finite element (FE) modeling has been used for the same purpose. These models are

usually built from clinical computed tomography (CT) images, which have coarse resolution (usual slice thickness is 0.5 mm) compared to articular cartilage thickness and do not allow proper discrimination of soft tissues. While there have been efforts to identify and include the location of articular cartilage using magnetic resonance imaging (MRI) (Gislason et al., 2010), most studies used constant thickness, e.g. 1 mm (Carrigan et al., 2003; Pillai et al., 2007; Guo et al., 2009) or half of the minimal bone-to-bone distance (Ezquerro et al., 2007; Fischli et al., 2009). However, such idealization has been shown to substantially influence the magnitude and distribution of computed contact pressure in the hip joint (Anderson et al., 2010). Furthermore, potential cartilage pre-stresses in the unloaded wrist have not been taken into account in previous models.

In summary some limitations of earlier studies are (i) relatively coarse imaging resolution, (ii) assumption of idealized cartilage thicknesses and (iii) neglected cartilage penetration existing when imaging the unloaded joint. The objective of the current study was therefore to evaluate the contact forces acting on the intact scaphoid in various functional wrist positions by means of an FE model of the human wrist and aimed to overcome the above limitations by resolving cartilage penetrations identified using high resolution CT image-based description of carpal bone positions and articular cartilage geometry.

2. Materials and methods

In full agreement with the ethical regulations of the Medical University of Vienna, a fresh frozen cadaveric human right forearm was taken from a female donor (age unknown) who had voluntarily donated her body to the Center of Anatomy and Cell Biology. The forearm was free of fractures and implants. All relevant cartilage layers were free of arthritis. The specimen was held frozen at -20°C and thawed at room temperature for 24 h prior to the experiment.

2.1. HR-pQCT scanning

The forearm was placed in a custom-made sample holder and fixed to it with three screws passed through the radius and the ulna (Fig. 1, left). Muscle forces during gripping were simulated using weights attached to wires sewed at the proximal ends of the tendons of seven isolated muscles (Fig. 1, right, Table 1). This setup was developed in a pilot study to allow gripping of a 0.5 kg object. Eight distinct positions were imposed by a polyester tape (Scotchcast Casting Tape, 3M) support: unloaded neutral (without weights) (UN), loaded neutral (LN), partial extension (PE), total extension (TE), partial flexion (PF), total flexion (TF), ulnar abduction (UA) and radial abduction (RA, shown in Fig. 1, left). Special weight settings were used in UA and RA positions by loading only those muscles that were assumed to contribute to these motions (Table 1).

An approximately 55 mm (660 slices) thick section of the wrist was scanned in each position by means of a high-resolution peripheral quantitative computed tomography system (HR-pQCT, XtremeCT, Scanco Medical AG, Switzerland, Fig. 1,

right) with the following settings: 60 kVp energy, 1 mA current, 100 ms integration time, 1536×1536 pixels image matrix and $82\text{ }\mu\text{m}$ isotropic nominal resolution.

2.2. μCT scanning

Following HR-pQCT image acquisition the forearm was dissected. The carpal complex was separated, the constituting bones were isolated and kept frozen till the further steps of the experiment. The radius and all carpal bones except for the pisiform were carefully cleaned of soft tissue remnants of ligament insertions. Cartilage layers were kept intact. In order to simulate the fully hydrated conditions present in the intact capsule of the cadaver wrist during HR-pQCT scanning, bones were submerged in Ringer's solution for 2 h at room temperature. This allowed swelling of articular cartilage to a fluid-saturated, macroscopically stress-free configuration and ensured thawing of the tissues. After removal of the solution, the bones were scanned with μCT (microCT40, Scanco) at $30\text{ }\mu\text{m}$ isotropic resolution using the following settings: 70 kVp, 114 mA, 200 ms integration time, 1024×1024 pixels image matrix.

2.3. FE modeling

The idea of the FE analysis was to resolve the overlaps between the cartilage layers of neighboring bones resulting from the μCT -based swelled (external mechanical force free) cartilage geometries and the HR-pQCT-based bone positions (intact wrist, carpal bones being compressed against each other).

2.3.1. Geometry from the CT images

First, following a similar idea as Snel et al. (2000), the HR-pQCT images of all wrist positions were registered (ITK, Kitware Inc., USA, www.itk.org to the LN position by taking the scaphoid as the basis. The spatial rigid registration identified an optimal transformation between the two input images by considering the grayscale values of all relevant voxels (Boyd et al., 2006). This procedure provided information about how the other bones were situated relative to the scaphoid in each investigated wrist position (Fig. 2).

In the second step, articular cartilage meshes of all bones were created in the LN position. The μCT image of each bone was registered with the corresponding image region of the LN position HR-pQCT image with the same approach described above. Using an in-house image fill algorithm (Pahr and Zysset, 2009), the external boundary of soft tissue as well as the interface between bone and soft tissue were identified (Fig. 3). Triangular surface mesh

Table 1

Magnitude of weights (in kg) applied on the muscles in case of the different wrist positions, which are: LN: loaded neutral, PE: partial extension, TE: total extension, PF: partial flexion, TF: total flexion, UA: ulnar abduction and RA: radial abduction.

Muscle name	LN, PE, TE, PF, TF	UA	RA
Flexor carpi radialis	1	0	1
Flexor carpi ulnaris	1	1	0
Extensor carpi radialis	2	0	2
Extensor carpi ulnaris	1	1	0
Extensor pollicis brevis and Abductor pollicis longus	1	0	1
Flexor pollicis longus	0.5	0	0
Flexor tendons of digits II–V	0.5	0	0.5



Fig. 1. Left: positioning and fixation of the forearm within the custom made HR-pQCT sample holder, fixed with screws (#). The figure shows the wrist in radial abduction. The white material (*) is plastic cast roll which was used to impose the wrist position and stabilize it during scanning. Right: sample holder placed into the HR-pQCT scanner with weights simulating muscle forces.

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