Journal of Biomechanics 47 (2014) 2989–2994

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Finite element simulation of the mechanical impact of computer work on the carpal tunnel syndrome

Dionysios E. Mouzakis [a,*], George Rachiotis [b], Stefanos Zaoutsos [a], Andreas Eleftheriou [c], Konstantinos N. Malizos [d]

[a] Department of Mechanical Engineering, Technological Educational Institute of Thessaly, 41110 Larissa, Greece
[b] Department of Hygiene and Epidemiology, Faculty of Medicine, School of Health Sciences, University of Thessaly, Larissa, Greece
[c] Department of Public Health, Technological Educational Institute of Athens, Athens, Greece
[d] Department of Orthopaedics and Musculoskeletal Trauma Surgery, Faculty of Medicine, School of Health Sciences, University of Thessaly, Larissa, Greece

ARTICLE INFO

Article history:
Accepted 4 July 2014

Keywords:
Computer work
Finite element analysis
Carpal tunnel syndrome
Biomechanics
Median nerve

ABSTRACT

Carpal tunnel syndrome (CTS) is a clinical disorder resulting from the compression of the median nerve. The available evidence regarding the association between computer use and CTS is controversial. There is some evidence that computer mouse or keyboard work, or both are associated with the development of CTS. Despite the availability of pressure measurements in the carpal tunnel during computer work (exposure to keyboard or mouse) there are no available data to support a direct effect of the increased intracarpal canal pressure on the median nerve.

This study presents an attempt to simulate the direct effects of computer work on the whole carpal area section using finite element analysis. A finite element mesh was produced from computerized tomography scans of the carpal area, involving all tissues present in the carpal tunnel.

Two loading scenarios were applied on these models based on biomechanical data measured during computer work. It was found that mouse work can produce large deformation fields on the median nerve region. Also, the high stressing effect of the carpal ligament was verified. Keyboard work produced considerable and heterogeneous elongations along the longitudinal axis of the median nerve. Our study provides evidence that increased intracarpal canal pressures caused by awkward wrist postures imposed during computer work were associated directly with deformation of the median nerve. Despite the limitations of the present study the findings could be considered as a contribution to the understanding of the development of CTS due to exposure to computer work.

1. Introduction

Carpal tunnel syndrome (CTS), the most common of the entrapment neuropathies, is a clinical disorder resulting from the compression of the median nerve at the wrist (Dawson et al., 1990). The evidence that computer use can cause CTS is mixed. There exists some evidence that using a computer mouse can be associated with the development of CTS. It has been reported that active use of the mouse elevated the pressure in the carpal tunnel up to 30 mm Hg (Rempel et al., 1998). Moreover, Keir and co-workers found that wrist extension and fingertip force applied to depress the button may account for the increased carpal tunnel pressure during computer mouse use (Keir et al., 1999). However, they suggest that the shape of the different mice tested had no differential effect on wrist postures and carpal tunnel pressure. Furthermore, contradictory results have been published concerning the association of the use of computer keyboard and carpal tunnel syndrome. Two systematic reviews reported either that the balance of evidence did not indicate an important association between keyboard and carpal tunnel syndrome, or that there is insufficient epidemiological evidence that computer work causes CTS (Palmer et al., 2007; Thomsen et al., 2008). Nevertheless, it has been stated that the question of whether intense keyboard use is associated with an increased or decreased risk of CTS is still unanswered (Rempel and Gerr, 2008). Notably, a laboratory study of healthy subjects typing at various actual wrist postures indicated carpal tunnel pressures ranged between 1.9 and 4.0 kPa (Rempel et al., 2008).

To our knowledge, there are limited data on the simulation of the carpal tunnel and median nerve stress and strain fields, or large elongations experienced by them. One of these works refers to a full simulation of the carpal area based on CT scan images, in

---

[*] Corresponding author. Tel.: +30 2410 684 556.
E-mail address: mouzakis@teilar.gr (D.E. Mouzakis).

http://dx.doi.org/10.1016/j.jbiomech.2014.07.004
0021-9290/

which the authors studied the effects of elongation of the transverse carpal ligament (Guo et al., 2007). In a similar investigation by finite element analysis, the effect of damage to carpal ligaments and the movement of carpal bones were studied (Javanmardian and Haghpanahi, 2010). In the most relevant study, anatomical image-based human carpal tunnel finite element (FE) models were constructed to enable the study of median nerve mechanical insult. It was found that large deformation, and (i.e.) multi-body contact between the nerve, the nine digital flexor tendons and the carpal tunnel boundary characterized the interactions within the carpal tunnel (Ko and Brown, 2007; Lin, 2009). The authors concluded that this was probably the main mechanism associated with the development of carpal tunnel syndrome. However, the methodology of these works employed rheological models with fluid mechanics (Ko and Brown, 2007; Lin, 2009). Despite, the availability of pressure measurements in the carpal canal during computer work (exposure to keyboard or mouse) there are no data to support a direct effect of the increased intracarpal canal pressure on the median nerve (Thomsen et al., 2008; Keir et al., 1999). Interestingly, computer keyboard typing effects on the time-dependent force response of the human fingertip have also been evaluated using finite element modeling (Wu et al., 2003).

This study attempts to contribute to the understanding of the carpal syndrome by simulating the impact of increased intracarpal canal pressures caused by computer work on carpal tunnel and specifically on the median nerve. The first step of this study was to synthesize a full 2D and pseudo-3D anatomical finite element model of the whole wrist section, with all the load-bearing tissues present, including the wrist bones. Secondly, this study aimed at applying real work-load scenarios of Computer use (keyboard and mouse) on the finite element model, in order to reach conclusions regarding the actual loading mechanism of the carpal tunnel and the median nerve during computer work.

2. Methodology – finite element modeling procedures

2.1. Two and three dimensional carpal models

A CT scan (front axial view) obtained from a public domain magnetic resonance imaging (MRI) DICOM-type image library [http://pubimage.hcuge.ch:8080/WRIX.zip, Hôpitaux Universitaires de Genève] was adopted as typical for the geometry of the carpal section. The CT monochromatic 16 bit-image at a resolution of 256 × 256 pixels, (pixel spacing 0.39×0.39 mm^2) was further digitized and each of the actual different tissue types (skin, muscles, bones, connective tissue, tendons, nerves, synovial tissue, ligaments), excluding blood vessels, corresponding to the section, was separately plotted and meshed by triangular elements. The triangular meshing of the model was performed by employing the NETGEN algorithm (©Joachim Schoeberl) which is incorporated as a separate tool into the FE-software (Lisa-Fet ver. 7.7.0, Sonnenhof Holdings). The mechanical properties, namely elastic modulus and Poisson's ratio, of the triangular elements, were obtained through cross-verification from the existing literature, and are presented in Table 1. The final 2D model resulted in 9490 triangular 6-node plate (Tri6) elements with a total of 19131 nodes. Nominal element thickness was set at 2 mm. The Tri6 elements are linear strain elements since this model was designed for linear elastic analysis and mid-side elements ensure higher accuracy. The boundary conditions applied to the 2D model allowed free rotation, of the carpal bones on the X–Y plane, but no relative movement in any axis. These boundary conditions are meant to simulate the free hand movement limitations during computer work.

The tissues involved in the carpal area from skin to median nerve are viscoelastic and present a hyper-elastic behavior. Their mechanical properties are difficult to determine as such. By finite element analysis, the parameters of the viscoelastic-hyperelastic properties of transverse carpal ligament (Main et al., 2012) and also of the digital flexor tendons and the median nerve respectively (Main et al., 2011) were described in detail. These works might contribute to an even more accurate finite element model of the full carpal section sometime in the near future.

The model was linear elastic, though, neither viscoelastic nor hyper-elastic since these properties shall be the objects of future analysis in coupled models.

The analysis performed was static-linear elastic. The two-dimensional (2D) model produced by the above methodology is shown in Fig. 1. The meshed FE model corresponds exactly to the actual life-size dimensions. Also, the 2D model was extruded by making use of the FE software preprocessor tools into a pseudo-three dimensional model as shown in Fig. 2. The total 3D model thickness was set at 25 mm by subdivision in 5 slices of 5 mm each. There were 50 division points (nodes) along the 360° perimeter used. The final 3D model resulted in 83660, wedge 6-node elements and 46838 nodes. The wedge 6-node (Wedge6) elements were automatically produced by the software 3D-mesh function. As in each pseudo-model, the 3D representation/image does not really show the actual anatomical details. The pseudo-3D model is produced by parallel projection of the very realistic 2D section. Nevertheless, since it is of small thickness, the authors believe that this provides a relatively good insight into the carpal region loading response, until a fully realistic 3D anatomical model is employed in further studies. In particular, very sophisticated and detailed wrist FEA models have been reported in the literature in other studies (Guo et al., 2007,2009; Fischli, et al., 2009, Gíslason et al., 2010; Bajuri, et al., 2012), which could be utilized in future work.

In order to produce the 3D-model carpal area movement all degrees of freedom were set as zero, on all nodes of the cross section visible on the left side (proximal slice), in Fig. 2.

2.2. Carpal models loading scenarios

The carpal section loading scenarios were designed so as to imitate, as much as possible, actual results obtained from researchers who have studied real-life load cases and strains experienced by the carpal tunnel area. The following two scenarios were used in the carpal models FE analysis, as presented in Table 2:

1. 2D A: 30 mm Hg internal pressure (Z-axis – pressure) on the carpal tunnel area (computer mouse) and applied on every cell node of the FE-2D model.

This 2D scenario simulates use of a typical computer mouse. The actual pressure has been measured during use of such a mouse (Rempel et al., 1998).

2. 3D C (computer keyboard): Upward bending of the carpal end by imposing a 10 mm vertical displacement constraint (U_y) on the free end of the model (distal slice), plus the application of an internal hydrostatic pressure of 17 mmHg. This actual pressure was determined during keyboard stroke motions (Rempel et al., 1998). The convergence in both the 2D and the 3D models was checked by subdivision of the elements in the initial models in two sub-elements and re-solving of the models. The differences in the solutions were below statistically significant levels.

3. Results

Fig. 3 illustrates the results on the total displacements vector experienced by the carpal area. Large displacements that reach up to almost 6 mm were observed inside the carpal tunnel region. In this case, the median nerve area (indicated by arrow), is subjected to differential involuntary axial elongation of a magnitude of ca. 2.5 mm. This is the simplest effect on the median nerve following exposure to computer mouse. This repeated longitudinal elongation

Table 1
Mechanical properties of the tissues used in carpal section model.

Tissue type	Young's modulus [MPa]	Poisson's ratio [dimensionless]	Sources
Bone	10,000	0.30	Pistoia et al. (2002)
Skin	0.1	0.48	Liang and Boppart (2010), and Li et al. (2012)
Muscle	0.045	0.5	Kot et al. (2012), Ogneva and Ushakov (2012), and Wells and Liang (2011)
Tendons	300	0.55	Maganaris and Paul (1999), Silver and Christiansen (1999), and Kubo et al. (2001)
Connective tissue	0.1	0.5	Silver and Christiansen (1999), and Silver et al. (2003)
Synovial tissue	0.03	0.5	McKee et al. (2011)
Ligament	250	0.5	Hirokawa and Tsuruno (2000)
Nerve	4.5	0.49	Reese et al. (2010), and Borschel et al. (2003)