SOFTWARE PLATFORM FOR VISUALIZATION AND EVALUATION OF CARPAL TUNNEL SYNDROME

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Abstract: Carpal tunnel syndrome (CTS) is one of the most common peripheral neuropathies due to the compression of the median nerve. Improvements in magnetic resonance imaging have allowed visualization of the anatomy of the carpal tunnel and the possibility of assessing eventual abnormalities associated with CTS. This work presents a software platform for interactive visualization and enhanced evaluation of the carpal tunnel syndrome (CTS), based on MRI. The software platform provides a fully scalable real-time 3D reconstruction of the tendons and the median nerve, allowing multiplanar reformatting, realistic visualization of the integrity of myelin sheath, and colour enhancement, without the use of contrast agents. The software platform is based on a methodology which provides metrics and measurement tools for different parameters, including median nerve location, size and flattening, but also nerve adjacency and local deformation shape measures. The proposed methodology was experimentally evaluated. The group of 60 persons (half of whom were patients with CTS) were involved in the evaluation process, conducted by a radiologist with more than 15 years of experience in the field, who was blinded to the clinical information of the patients. The results of this study showed that the developed software and the MR imaging of the carpal tunnel structures can be used as a valuable tool for CTS evaluation and detection, and it can also help in planning of surgery or revealing the CTS etiology.

Key words: MRI visualization, 3D volume rendering, carpal tunnel syndrome, evaluation, metrics.

Introduction

The carpal tunnel (Figure 1) is a semi-rigid passageway, approximately 6 cm long, on the palmar side of the wrist, that connects the forearm to the middle compartment of the deep plane of the palm.
It is bounded on the dorsal, radial, and ulnar sides by the carpal bones and on the volar side by the transverse carpal ligament. This ligament extends from the tuberosities of the trapezium and scaphoid on the radial side, to the hook of the hamate and pisiform on the ulnar side [1]. Nine flexor tendons of the fingers and the median nerve pass through the confines of the carpal tunnel and then diverge to the fingers in order to supply function, feeling and movement. The median nerve innervates the thumb, index, and long fingers as well as the radial side of the ring finger. The superficial tendons flex the proximal interphalangeal joint of each finger, and the deep tendons flex the distal interphalangeal joint [2].

![Figure 1 – Anatomy of the carpal tunnel [21]](image)

Because of the rigidity of the boundaries of the carpal tunnel, any process that either increases the volume of the contents of the tunnel or decreases the size of the tunnel can result in symptoms.

Among the group of disorders, described as peripheral compression neuropathies, the carpal tunnel syndrome (CTS) is the most common one. These disorders occur because some peripheral nerves are compressed as a result of certain risk factors including superficial anatomic location, coursing through an area at higher risk of insult, or coursing along a narrow pathway through a bony canal [3]. Due to the anatomic position of the median nerve as it courses through the narrow carpal tunnel, it is at higher risk of insult than many other peripheral nerves.
CTS is characterized by tightness, discomfort, stiffness or pain on the anterior (front) side of the hands and wrists accompanied by tingling, numbness and/or paraesthesia affecting the thumb, index, middle and one half of the ring finger. In severe cases, the atrophy of the thenar eminence is most common due to restricted median nerve conduction and blood supply. Loss of muscle strength in the thumb, index and middle fingers is also very common [4]. Additional side-effects of carpal tunnel syndrome may include generalized aching, swelling, and diminished coordination of the fingers, especially when performing fine motor movements required for picking up small objects.

CTS affects 1 percent of the general population and 5 percent of the working population and it is usually observed between the 4th and 6th decades with a female to male ratio of 2.5 : 1.

The individuals who perform jobs that require repetitive or static flexion (no-movement) of the fingers and wrist are most at risk for developing CTS. Sustained activities that require unidirectional (one-way) movement patterns like repetitive or static flexion, along with having the wrist positioned at extreme angles, the use of vibration tools and machinery, and/or being in extreme temperatures, will increase the likelihood of developing a repetitive strain injury like carpal tunnel syndrome. This means that certain occupations have been identified as having an increased risk of CTS, including computer operators, secretaries, tennis players, musicians, construction workers, assembly line workers, housewives, truck drivers and teachers [5]. The impact of CTS symptoms are felt not only at work, but also at home and are associated with activities involving strength, such as pushing open a window or pushing up from an armchair, and activities involving grip strength, such as writing with a pen or pouring from a container to a glass [6].

According to the US Bureau of Labor Statistics, there were 11,950 formally reported cases of CTS involving lost work days in 2008 among government workers [7]. The economic burden on patients and their families and society in the form of direct and indirect costs, due to the CTS, is very large. The non-medical costs of a CTS case from compensation settlements and disability average $10,000 per hand. Include medical and indirect costs and the amount is elevated to $20,000 to $100,000 per hand [8]. The workers and their families must cope with inability to perform social activities and activities of daily living due to pain, clinical depression, and most significantly the long-term loss of earnings. Dimmitt [9] also noted that litigations represent an important part of the total cost of CTS with lawyers’ fees and other legal taxes accounting for 25% of costs. On the other hand, employers must deal with the indirect costs of production interruption, accident investigation, and the recruiting and training of a new worker to replace the impaired worker [10].
ding to the statistical data, in 1995, the economic cost of CTS per year in the United States was estimated to exceed $2 billion [11]. All these factors have increased the demand for rapid and accurate detection and diagnosis of CTS.

The American Academy of Orthopaedic Surgeons (AAOS) has published guidelines which state that a diagnosis of CTS should be made based on the history of the present illness, physical examination, and electrodiagnostic tests [12]. Recently, most studies have pointed out that imaging techniques may provide important information in entrapment neuropathies, particularly in cases of equivocal electrophysiologic studies [13, 14]. The median nerve was firstly visualized on sonography [15]. Because the attenuation difference between the median nerve and other structures within the tunnel are very restricted, sonography is not sensitive enough to visualize the carpal tunnel. Nor is computed tomography sensitive enough for imaging of the carpal tunnel structures [16].

Because of its excellent resolution of soft tissues, MRI has often been used in studying the anatomy of the carpal tunnel to assess possible abnormalities associated with CTS and has been considered as the best imaging modality. Therefore, in this work we are presenting an MRI software system that should help for CTS detection. To the best of our knowledge no prior software system that implements an integral set of tools and metrics, for CTS evaluation and detection, has been reported in the literature. The developed software system and its tools and metrics are evaluated and the results are presented.

Software architecture overview

The overall architecture of the developed software is presented in Figure 2. The proposed software architecture follows the Model – View – Controller pattern which decomposes the application into three functional parts: the model, the view and the controller.

A model represents an application’s data and contains the logic for accessing and manipulating that data. Any data that is part of the persistent state of the application reside in the model objects. In particular it implements software routines for reading DICOM files. It supports all kinds of DICOM image files: greyscale and colour, single-frame and multi-frame, JPEG-compressed (lossy and lossless), JPEG-2000-compressed (reversible and irreversible), RLE-compressed and ZIP-compressed studies. Special routines for reading and writing proprietary project files as well as routines for report generation and multimedia files generation are also implemented at this level. The service routines that a model exposes are generic enough to support even web-based clients. A
model’s interface exposes methods for accessing and updating the state of the model and for executing complex processes encapsulated inside the model. The model implements services for manipulation of three-dimensional volumetric data. To add robust interpretation of data, it provides volume reduction services that can be used to remove irrelevant parts of the volume and highlight the relevant ones. It includes techniques such as volume clipping planes, volume of interest definition, slabbing and masking. At this level image enhancement services are also implemented. They can help to reduce certain anomalies in the data due to the imperfection of the hardware. Due to the fact that the location, size, and shape of the tendons and the median nerve play a key role in CTS detection, image segmentation services are of particular importance. All model services are accessed by the controller for either querying or effecting a change in the model state. The model notifies the view when a state change occurs in the model.

The **Controller** component is the bridge between users and the application by receiving and handling all user events, such as keyboard and mouse inputs. This module knows which Model and View component to access. In order to handle a user event, the Controller component requests Model to process the new data and, at the same time, tells View component to update the visuals.

The **View** component is responsible for rendering the visual contents onto the screen. Also, View module does not have any reference to Controller component (independent of Controller). It only performs the rendering process when any Controller component requests it to update the visual. However, View component references to a certain Model component, because it must know where to obtain the data from, so that it can render the data on the screen. To

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**Figure 2 – Software architecture overview**

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provide the user with all the necessary tools for visualization, inspection and
analysis of the carpal tunnel content and CTS detection, a user-friendly GUI is
developed (Figure 3). As can be observed multiple different views are simulta-
neously added. Because of its efficient modularity, the components can be inter-
changeable and scalable so that the look-and-feel of the GUI can be custom-
mized without modifying the Model and Controller modules.

![GUI of the developed software](image)

**Figure 3 – GUI of the developed software [17]. It consists of an axial view
(where the segmentation is performed), a 3D view, MPR views and navigation plains.
Multi-plain volume clipping can help in analysing the wrist and CT structures**

**Materials and methods**

As the nerve shifts to a position interposed between tendons during
wrist flexion and extension, it is probable that mechanical insult would occur
during its extrusion between the loaded tendons [3]. Thus it is very useful to
know where the nerve is typically located in the carpal tunnel during various
wrist positions. In order to avoid lacerating the nerve during surgery, it is also
useful to determine whether bifurcation or trifurcation of the nerve exists within
the tunnel. Therefore, the developed software platform provides realistic 3D
visualization of the wrist from MRI, implements multiplanar reformatting and
3D navigation, which can be useful for identifying, visualizing the position and
displacement of the nerve and other CT structures (Figure 4), as well as tracking
their propagation along the tunnel.
In order to help the user to understand the volume data, to uncover important details in the wrist volume data, the software platform implements a real time visualization method based on GPU ray casting, which is capable of using multiple planes for convex volume clipping. Our approach allows the user to select an arbitrary number of clipping planes. Since the ray direction is computed in the eye coordinate system and its bounding box is defined in the world coordinates, the ray direction must be transformed back to the world system and the intersections must be computed in the world coordinate system. So, from analytical geometry, the parameterized equation of the ray can be defined as:

$$ P_w^\text{xyz} = P_{\text{eye}}^\text{xyz} + D_w^* t $$

where $P_w$ is the 4D homogeneous coordinates $(x, y, z, 1)$, $P_{\text{eye}}$ is the eye position (viewpoint) defined with its homogeneous coordinates $(x_{\text{eye}}, y_{\text{eye}}, z_{\text{eye}}, 1)$, $t$ is the distance from the eye position, $D_w$ is the normalized 3D vector of the ray direction $(x_d, y_d, z_d)$. According to the analytic geometry a plain can be defined as:

$$ Ax + By + Cz + D = S \cdot P_w = 0 $$

From Eq. 1 and Eq. 2 the intersection between the ray and the plain can be obtained as:

$$ t = -\frac{Ax_{\text{eye}} + By_{\text{eye}} + Cz_{\text{eye}} + D}{Ax_d + By_d + Cz_d} = -\frac{S \cdot P_{\text{eye}}}{S \cdot xyz \cdot D_w} $$

Since the clipping plane divides the convex volume into two parts, the volume that the normal of the plane points to is kept, whereas the other one is
visually discarded. Several planes are often used for convex volume clipping and each ray may have several intersections with clipping planes. How to select two points as start and end points from these intersections is a key problem to correctly implement convex clipping. In the case in which a ray is parallel to one of the planes, the eye point $P_{\text{eye}}$ will be in the visible part of the clipping plane $S$ if $S \cdot P_{\text{eye}} > 0$. If a ray is not parallel to a plane, there must be an intersection. Ray-plane intersections are classified into two categories: intersections with angles less than 90 deg. with the plane normal and intersections with angles greater than 90 deg. with the plane normal. From these angle values the start and the end points are calculated, so each ray can be traced to compute the volume integral from the start point to the end point on the GPU. Clipping planes can be moved in order to permit the user to analyze the whole wrist structure in 3D (Figure 3).

In addition to visualizing the location of the nerve, MRI is useful for studying the size and shape of the median nerve, carpal tunnel structures adjacency, carpal tunnel contents ratio, the local deformations of the median nerve surface tissue, and how these characteristics vary in normal subjects versus symptomatic patients. To determine these quantitative metrics, which can be used as CTS indicators, it is necessary to segment the carpal tunnel boundary, median nerve and tendons. Image segmentation is the problem of extracting (segmenting, cutting-out) foreground objects from background in an image. It is one of the most fundamental problems in computer vision. Fully automatic segmentation is still an open problem due to the wide variety of possible combinations of objects, and so it seems that the use of human "hints" is inevitable. Recently, interactive image segmentation has become more and more popular in the field of medical image segmentation. The goal of interactive segmentation is to extract object(s) from the background (or just split the image into continuous classes) in an accurate way, using user knowledge in a way that requires minimal interaction and minimal response time.

In order to obtain shape and location information about the individual digital flexor tendons, the median nerve, and the carpal tunnel, an interactive segmentation algorithm of the carpal tunnel structures in the axial plain was implemented. The algorithm is a modified version of the algorithm described in [24] and implemented using the dynamic programming methodology. This approach works well in a typical case where the foreground and background differ in appearance, as well as in challenging cases where the CT structure is clearly perceived, but the regions on both sides of the boundary are similar and cannot be easily discriminated. The final result is accurate, because it allows the user to directly enforce hard constraints on the boundary. The cross-sectional area of each structure inside the carpal tunnel was found by calculating the area inside each segmented structure boundary.
Numerous CTS studies have used MRI to quantify the size and shape of various structures within the carpal tunnel in order to identify pathological changes associated with CTS [18, 19]. Many studies have reported an enlargement and flattening of the median nerve as CTS indicators. The cross-sectional area is traditionally computed as the area of an ellipse fit of the median nerve and the flattening ratio as the major axis length divided by the minor axis length of the ellipse [20]. Some studies of normal carpal tunnels found the average cross-sectional area of the median nerve to be 7 mm² at the level of the pisiform and 8 mm² at the level of the hook of the hamate [18], and other studies reported 10 mm² at the pisiform and 9 mm² at the hook of the hamate [19]. On the other hand, several studies have found that patients with CTS typically have significantly flatter median nerves at the hook of the hamate than normal carpal tunnels, with ratios of 3.4 at the pisiform and 3.8 at the hook of the hamate [22]. However, another study found that there was no significant difference between the nerve flattening ratio of normal and CTS patient groups [23]. Therefore, we argue that the flattening ratio cannot be considered as a reliable metric, since two nerves may have completely different shapes visually, but have very similar flattening ratios. Instead, we propose a carpal tunnel contents ratio to be used as CTS evaluation metric. It can be defined as:

\[
CR = \frac{\sum_{i=1}^{9} St_i + Smn}{Sct}
\] (4)

Where \(St_i\) is the cross-sectional area of each of the nine tendons, \(Smn\) of the median nerve and \(Sct\) of the whole carpal tunnel. A larger ratio would indicate either enlarged tunnel contents or a smaller tunnel, and thus there would be less space for the median nerve, which could lead to its damage. In addition to traditional size and shape measures, a new MRI evaluation metric, which calculates the distance of the closest adjacent structure (tendon or carpal ligament) to the nerve boundary, was developed. A given structure was considered to be adjacent to the nerve if it was within 1mm of the boundary of the nerve. To identify local deformations, the boundary of each segmented tissue structure was discretized into equal length line segments. Analysis of the internal angles between consecutive segments was considered as an indicator for impingement (angles > 240°) or pinch (angles < 120°) occurrence. To visualize the deformations, the location of local pinches and impingements were highlighted in red and then they were compared to the adjacency data to determine when an adjacent structure was the cause of the nerve deformation (Fig. 5).

For better visualization of local deformations semi-transparent volume rendering of separate carpal tunnel structures was implemented. The opacity in the image is derived by the compositing equation given by Eq. 5.

\[
\alpha_{\text{accym}} = \alpha_6 (1 - \alpha_{\text{accym}}) + \alpha_{\text{accym}}
\] (5)
where $\alpha_o$ is the opacity value. Each sample point contributes to the final image in different degrees and its contribution or visibility $\alpha_v$ is defined by $\alpha_o(1-\alpha_{\text{accum}})$. For each ray, we compute the voxel opacity $\alpha_o$ (importance) of every sample point on the ray and its visible opacity $\alpha_v$.

![Figure 5 – Semi-transparent volume rendering.](image)

The software is implemented using a native DirectX and C# .NET environment. Software evaluation was performed on a PC with windows7 OS, 4GB RAM, AMD Athlon™ II X4 620 Processor 2.6GHz, NVidia GeForce GTS 250 graphic card. The study for software and algorithm validation included 30 patients with CTS and 30 healthy volunteers (control group). MRI findings of 30 CTS wrist volumes and 30 normal wrist volumes, including 40 T1 weighted axial plane images, were compared. The mean age of the CTS diagnosed patient group was 45.43 with a standard deviation of 17.25 and the mean age of the control group was 43.18 with standard deviation of 11.55. There was no significant difference in terms of age between the two groups ($p > 0.05$).

The images were obtained by the wrist coil of a 1.5T MRI scanner. The slices were 3 mm thick with 1 mm gap intervals; matrix size was 256 × 256; FOV was 160 mm.

All examinations were evaluated by a radiologist with more than 15 years of experience within the field. the radiologist was blinded to the clinical information on the patients or test persons. Segmenting the 9 digital flexor tendons, median nerve, and carpal tunnel boundary on images spanning the carpal tunnel took on average 1 minute per cross-sectional image, depending on the image quality. To speed up the segmentation procedure and 3D reconstruction,
the mask created on a single axial slice can be copied and positioned on the neighbouring slices. Then, if necessary, manual editing by the user was also enabled.

Results and discussion

It was reported that in all cases (even in the most complicated) the realistic 3D visualization was very helpful for CT contents analysis and can be used as an important tool in CTS detection and evaluation. In particular, it was reported that the multiplanar reformatting and clipping help to identify and to follow the nerve and tendons propagation along the carpal tunnel. Using the clipping feature, the radiologist successfully detected the bifurcation of the nerve which was present in one of the patients. Using the nerve size metric tool, the radiologist found the cross-sectional area of the median nerve in normal patients to be 9–10 mm\(^2\) at the pisiform and 10–11.2 mm\(^2\) at the hook of the hamate, while in CTS patients the median nerve size at the hook of the hamate varies between 14–17 mm\(^2\).

Carpal tunnel contents ratios in the sections through the pisiform and the hook of the hamate were calculated as a validation measure using the cross-sectional areas of the structures on each section. This ratio ranged from 35–66% at the pisiform and 42–65% at the hamate. These values closely overlap the range typically reported (45–60%) at the narrowest part of the tunnel (the hamate), indicating that the resulting models were realistic and consistent with prior work. The results also showed the CTS patient group had more local nerve deformations (pinch and impingement) than the normal subject group. This was especially evident at the hook of the hamate, compared to the pisiform, which corresponded to the largest change in the percent adjacency of the nerve.

Conclusion

According to the results of this study, we believe that the developed software and the MR imaging of the carpal tunnel structures can be used as a valuable tool for CTS evaluation and detection, and can also help in the planning of surgery or revealing the CTS etiology.

REFERENCES


Резиме

СОФТВЕРСКА ПЛАТФОРМА ЗА ВИЗУЕЛИЗАЦИЈА И ЕВАЛУАЦИЈА НА КАРПАЛ ТУНЕЛ СИНДРОМ

Штериев Ф. 1, Коцеска Н. 2, Коцески С. 2

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Апстракт: Карпал тунел синдромот е една од најчестите периферни невропатии која се јавува како резултат на компресија на средишниот нерв (median nerve). Напредокот во полето на магнетната резонанца овозможува визуелизација на анатомијата на карпал тунелот и можност за проценка на евентуални абнорналности поврзани со карпал тунел синдромот. Во рамките на овој труд е претставена софтверска платформа за интерактивна визуелизација и за подобро евалуација на карпал тунел синдромот, базирана на MRI. Софтверската платформа обезбедува потполно флексибилна и скалабилна 3D реконструкција во реално време на тетивите и средишниот нерв, овозможувајќи мули-планарно реформатирање, реалистична визуелизација на интегритетот на миелинската обвивка, и подобри реалистични бои, без употреба на никакви контрастни агенти. Имплементираната методологија обезбедува метрики и мерни алатки за различни параметри вклучувајќи и: локација на средишниот нерв, определување на неговата големина, спласнување, но исто така и анализа на последиците од неговото доближување до соседните структури како и мерки за определување на локалните деформации на формата. Предложената методологија беше експериментално евалуирана од страна на радиолог со повеќе од 15 години искуство во областа. Евалуацијата беше извршена на група од 60 пациенти, од кои половината со карпал тунел синдром, но без каква било
претходна информация за клиничката с состојба на пациентите. Резултатите од ваквата евалуација покажа дека развиениот софтвер може да се користи како вредна алатка во евалуацијата и детекцијата на карпал тунел синдромот како и за откривање на неговата етиологија.

Ключни зборови: MRI визуелизација, 3D волуменско рендерирање, карпал тунел синдром, евалуација, метрики.

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