Annals of Anatomy 193 (2011) 64–70

Contents lists available at ScienceDirect

Annals of Anatomy

journal homepage: www.elsevier.de/aanat

RESEARCH ARTICLE

Three-dimensional surface models of detailed lumbosacral structures reconstructed from the Visible Korean

Dong Sun Shin[a], Min Suk Chung[a], Jin Seo Park[b], Hyung Seon Park[c], Seung-Bock Lee[c], Sang-Ho Lee[c], Ho-Nam Choi[c], Martin Riemer[d], Heinz Handels[e], Jong Eun Lee[f,g], Wonsug Jung[a,g,*]

[a] Department of Anatomy, Ajou University School of Medicine, Worldcup-ro 164, Suwon 443-749, Republic of Korea
[b] Department of Anatomy, Dongguk University College of Medicine, 707 Seokjang-dong, Gyeongju 780-714, Republic of Korea
[c] Korea Institute of Science and Technology Information, 335 Gwahangno, Yuseong-gu, Daejeon 305-806, Republic of Korea
[d] Department of Medical Informatics, University Medical Center Hamburg-Eppendorf, Martinistr. 52, D-20246, Hamburg, Germany
[e] Institute of Medical Informatics, University of Lübeck, 23538, Ratzeburger Allee 160, Lübeck, Germany
[f] Department of Anatomy, Yonsei University College of Medicine, Seoul, South Korea
[g] BK 21 Project for Medical Science, Yonsei University College of Medicine, Seoul, South Korea

ARTICLE INFO

Article history:
Received 19 April 2010
Received in revised form 23 August 2010
Accepted 3 September 2010

Keywords:
Visible Human Projects
Cadaver
Cross-sectional anatomy
Lumbosacral region
Cauda equina
Ligaments
Three-dimensional imaging

SUMMARY

Unlike volume models, surface models representing hollow, three-dimensional images have a small file size; allowing them to be displayed, rotated, and modified in real time. Therefore, surface models of lumbosacral structures can be effectively used for interactive simulation of, e.g., virtual lumbar puncture, virtual surgery of herniated lumbar discs, and virtual epidural anesthesia. In this paper, we present surface models of extensive lumbosacral structures which can be used in medical simulation systems. One-hundred and thirty-eight chosen structures included the spinal cord, lumbar and sacral nerves, vertebrae, intervertebral discs, ligaments, muscles, arteries, and skin. The structures were outlined in the sectioned images from the Visible Korean. From these outlined images, serial outlines of each structure were stacked. Adopting commercial software (3D-DOCTOR, Maya), an advanced surface reconstruction technique was applied to create a surface model of the structure. In the surface models, we observed the anatomical relationships of the lumbosacral structures (e.g., cauda equina and ligaments) in detail. Additionally, the portions of some spinal nerves that could not be outlined were drawn and added to the surface models. These constructed models will hopefully facilitate development of high quality medical simulation of the lumbosacral region.

1. Introduction

Three-dimensional models of lumbosacral structures can be used in the development of a variety of virtual lumbosacral procedures as well as educational programs. Unlike volume models, hollow surface models with small file size can be distributed, opened, rotated, and modified in real time, even online. These features make the surface models suitable for an interactive simulation system (Uhl et al., 2006). The accurate surface models can be obtained by surface reconstruction after stacking serial outlines of the structures. However, detailed structures such as the cauda equina are difficult to identify and outline from the computed tomographs (CTs) and magnetic resonance images (MRIs). To overcome this problem, the cross-sectional images of a cadaver from the Visible Korean can be utilized (Park et al., 2005b). But even in the sectioned images, small structures cannot be perfectly identified. Such structures should be drawn stereoscopically to complete a set of surface models. In addition, surface reconstruction on commercially available software requires input from medical experts (Park et al., 2007; Shin et al., 2009a,b). Therefore, the technique used for developing such models would benefit from automation.

The purpose of this research has been to construct surface models of detailed lumbosacral structures to establish a virtual reality simulator that can be used in clinical practice. The surface models to be distributed will be accompanied by source data such as sectioned images and outlined images, all of which correspond to one another. To achieve this goal, we outlined as many lumbosacral structures as possible in the sectioned images from the Visible Korean. Surface reconstruction of the outlined structures was performed using a new technique. With the surface models, we investigated the

* Corresponding author. Tel.: +82 31 219 5032; fax: +82 31 219 5039.
E-mail addresses: sds@ajou.ac.kr (D.S. Shin), dissect@ajou.ac.kr (M.S. Chung), park93@dongguk.ac.kr (J.S. Park), seonpark@kisti.re.kr (H.S. Park), sblee@kisti.re.kr (S.-B. Lee), shlee@kisti.re.kr (S.-H. Lee), hnchoi@kisti.re.kr (H.-N. Choi), riemer@uke.uni-hamburg.de (M. Riemer), handels@imi.uni-luebeck.de (H. Handels), jelee@yuhs.ac (J.E. Lee), wonsug@ajou.ac.kr (W. Jung).

0940-9602/$ – see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.aanat.2010.09.001

anatomical features such as relationship of the spinal nerves and ligaments to the vertebral column. In addition to these constructed surface models, we manually drew the structures which were not outlined.

2. Materials and methods

During the previous Visible Korean study, the T1 weighted MRIs (GE Signa Horizon 1.5-T MRI System, Milwaukee, WI) and CTs (GE High Speed Advantage, Milwaukee, WI) of a male cadaver (age, 33-years; height, 1.64 m; weight, 55 kg) were acquired at 1 mm intervals. The cadaver was then serially sectioned at 0.2 mm intervals; the sectioned surfaces were photographed to create horizontal sectioned images (tag image file format (TIFF); pixel size, 0.2 mm) (Park et al., 2005b). Among them, the sectioned images including the lumbosacral region were chosen from the superior end of the eleventh thoracic vertebra to the inferior end of the hip bones. The 11th thoracic vertebra was included because the first lumbar nerve was known to emerge from the spinal cord at this level. Subsequently, only every fifth image, resulting in 372 sectioned images (intervals, 1 mm) were chosen for outlining to reduce the amount of segmentation work and data.

2.1. Outlining of structures (Photoshop)

The lumbosacral structures to be delineated were chosen. All sectioned images were first printed onto paper in gray scale. Large and well-demarcated structures (e.g., bones) could be delineated directly on the sectioned images. However, small and indefinite structures (e.g., peripheral nerves, ligaments) were delineated after demarcating them on printed paper with colored pens. The use of paper permitted the images to be readily flipped back and forth to identify and trace the structures. During the drawing process on paper, we finally determined the lumbosacral structures and relevant structures that could be outlined on the sectioned images. In addition, we selected the structures that could not be outlined, but should be shown later, to establish 138 complete surface models (Table 1).

Table 1
One-hundred and thirty-eight lumbosacral structures outlined on the sectioned images and reconstructed to build the surface models.

Systems	Structures
Skeletal (11)	Thoracic vertebrae (T XI–T XII), lumbar vertebrae (L I–L V), sacrum, coccyx, hip bones[a]
Articular (25)	Interspinous ligaments (L I–L II, L II–L III, L III–L IV, L IV–L V, L V–sacrum), ligamenta flava (L I–L II, L II–L III, L III–L IV, L IV–L V, L V–sacrum), supraspinous ligament, anterior longitudinal ligament, posterior longitudinal ligament, intervertebral discs (T XI–T XII, T XII–L I, L I–L II, L II–L III, L III–L IV, L IV–L V, L V–sacrum), nucleus pulposus (L IV–L V)[c], sacrotuberous ligaments[a], sacrospinous ligaments[a]
Muscular (20)	Iliocostalis[a], longissimus[a], spinalis[a], transversospinalis[a], intertransversarii[a], quadratus lumborum[a], psoas major[a], piriformis[a], obturator internus[a], obturator externus[a]
Vascular (12)	Common iliac arteries[a], internal iliac arteries[a], obturator arteries[a], superior gluteal arteries[a], inferior gluteal arteries[a], internal pudendal arteries[a,b]
Nervous (69)	Dura mater, spinal cord, terminal filum[c], anterior roots of lumbar nerves (L1–L5)[a,b], posterior roots of lumbar nerves (L1–L5)[a,b], anterior rami of lumbar nerves (L1–L5)[a,b], anterior roots of sacral nerves (S1–S4)[a], posterior roots of sacral nerves (S1–S4)[a], anterior rami of sacral nerves (S1–S4)[a,b], superior gluteal nerves[a,b], inferior gluteal nerves[a,b], obturator nerves[a,b], femoral nerves[a,b], pudendal nerves[a,b], sciatic nerves[a,b]
Integumentary (1)	Skin

[a] Bilateral structures.
[b] Structures, partly pictured in the surface models.
[c] Structures, wholly pictured in the surface models.

The spinal nerves, exceptionally detailed among the lumbosacral components, were traced in the sectioned images as follows. Each lumbar nerve was identified with the help of the corresponding intervertebral foramen. For example, the second lumbar nerve was found between the second and third lumbar vertebrae. In the present study, the portion in the intervertebral foramen was regarded as the spinal ganglion of the lumbar nerve (Fig. 1a and b).

Each lumbar nerve was then traced both proximal and distal to the intervertebral foramen. The anterior and posterior roots of the lumbar nerve, which formed the cauda equina, were pursued proximally (Fig. 1a and b) up to the level of the first lumbar vertebra. Above this level, every root tends to divide into several rootlets, which were scarcely identifiable (Fig. 3).

Distal to the intervertebral foramen, only the anterior ramus of each lumbar nerve was pursued as the thin posterior ramus was not recognizable. The pursuit did not advance far because the color and texture of a nerve was similar to that of the surrounding tissue and this anterior ramus further divided to become part of the lumbosacral plexus. On the other hand, thick branches of the plexus being the superior gluteal, inferior gluteal, obturator, femoral, pudendal, and sciatic nerves could be outlined (Figs. 2b and 3a).

Similarly each sacral nerve was identified at the anterior sacral foramen and traced proximally and distally. Differences in the sacral nerve compared to the lumbar nerve were as follows: The anterior sacral foramen contained the anterior ramus of the sacral nerve, while the sacral canal included the spinal ganglia (Fig. 1c and d). The roots, which also formed the cauda equina, could be followed upwards almost to the spinal cord since the sacral nerve roots were not split into numerous rootlets (Fig. 3a).

After the drawing job on printed paper, sequential computer images were constructed using adequate software packages. The outlining and color-filling procedures were performed on Photoshop CS3 version 10 (Adobe Systems, Inc., San Jose, CA, USA); surface reconstruction was completed on 3D-DOCTOR version 4 (Able software, Corp., Lexington, MA, USA). The surface models were refined, assembled in their place to be observed, and additionally pictured on Maya version 2009 (Autodesk, Inc., San Rafael, CA, USA) (Table 2).

While referring to the paper drawings, the lumbosacral structures of the sectioned images were outlined on a computer screen. The file format of the sectioned images was converted from TIFF into Photoshop document (PSD) (Table 2). To enhance the automation of delineation, a 'median' or 'sharpen' filter was applied to the sectioned images. This resulted in the enhanced contrast between target structures and the background. The lumbosacral structures were then outlined automatically, semi-automatically, or manually in sequence (Park et al., 2005a; Shin et al., 2009b).

Table 2
Sequential procedures of outlining and surface reconstruction.

Procedures (software packages)	Resultants (file extensions)
1. Outlining of structures (Photoshop)	Outlined images (PSD)
2. Filling of outlines with colors (Photoshop)	Color-filled images (TIFF)
3. Surface reconstruction of outlined structures (3D-DOCTOR)	Reconstructed surface models (DXF)
4. Refining and assembling of surface models (Maya)	Refined and assembled surface models (MB)
5. Anatomic observation of surface models (Maya)	Captured views (TIFF)
6. Picturing of not-outlined structures (Maya)	Pictured surface models (MB)