

Received: 2016.10.12
Accepted: 2016.11.03
Published: 2017.05.22

Visualization of Penile Suspensory Ligamentous System Based on Visible Human Data Sets

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

BCEF 1 **Xianzhuo Chen***
BCD 2 **Yi Wu***
AG 1 **Ling Tao***
BCD 3 **Yan Yan**
CD 4 **Jun Pang**
BCD 2 **Shaoxiang Zhang**
A 1 **Shirong Li**

1 Department of Plastic and Reconstructive Surgery, Southwest Hospital, Third Military Medical University, Chongqing, P.R. China
2 Institute of Digital Medicine, College of Biomedical Engineering, Third Military Medical University, Chongqing, P.R. China
3 Department of Stomatology, Affiliated Hospital of North Sichuan Medical College, Nanchong, Sichuan, P.R. China
4 Institute of Anorectal Diseases, North Sichuan Medical College, Nanchong, Sichuan, P.R. China

* These authors contributed equally to this work

Corresponding Author: Shirong Li, e-mail: Shirong.Li1953@gmail.com

Source of support: This work was supported by the National Science Foundation of China (No. 81301645)

Background: The aim of this study was to use a three-dimensional (3D) visualization technology to illustrate and describe the anatomical features of the penile suspensory ligamentous system based on the Visible Human data sets and to explore the suspensory mechanism of the penis for the further improvement of the penis-lengthening surgery.

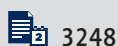
Material/Methods: Cross-sectional images retrieved from the first Chinese Visible Human (CVH-1), third Chinese Visible Human (CVH-3), and Visible Human Male (VHM) data sets were used to segment the suspensory ligamentous system and its adjacent structures. The magnetic resonance imaging (MRI) images of this system were studied and compared with those from the Visible Human data sets. The 3D models reconstructed from the Visible Human data sets were used to provide morphological features of the penile suspensory ligamentous system and its related structures.

Results: The fundiform ligament was a superficial, loose, fibro-fatty tissue which originated from Scarpa's fascia superiorly and continued to the scrotal septum inferiorly. The suspensory ligament and arcuate pubic ligament were dense fibrous connective tissues which started from the pubic symphysis and terminated by attaching to the tunica albuginea of the corpora cavernosa. Furthermore, the arcuate pubic ligament attached to the inferior rami of the pubis laterally.

Conclusions: The 3D model based on Visible Human data sets can be used to clarify the anatomical features of the suspensory ligamentous system, thereby contributing to the improvement of penis-lengthening surgery.

MeSH Keywords: **Imaging, Three-Dimensional • Ligaments • Penis • Visible Human Projects**

Full-text PDF: <http://www.medscimonit.com/abstract/index/idArt/901926>



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Background

In humans, the penis is supported in the prepubic position in its flaccid and erect states by a support system called the penile suspensory ligamentous system [1]. This system consists of 3 components: the fundiform ligament of penis, suspensory ligament of penis, and arcuate pubic ligament [2]. Its function is to suspend the flaccid penis in the prepubic position and support the erect penis in an upright position [3]. In the plastic and reconstructive surgery field, the suspensory ligamentous system is clinically significant because of its relationships to the performance of penis-lengthening surgery. Although various penis-lengthening procedures have been developed to improve this surgery in recent years [4–6], the most widely used technique is the transversal incision of the fundiform ligament and partial division of the suspensory ligament from the pubic symphysis to allow forward movement of the root of the penis. This technique may enable the penis to extend outward to achieve the effect of elongation [7, 8]. However, an extensive release of the above ligaments may cause the penis to lose its stability and perhaps lose its upward orientation so that it is unable to penetrate the vagina and requires manual assistance [9].

Since the suspensory ligamentous system plays a crucial role in maintaining stability of the penis, various studies have been performed in the past few decades to describe this system's anatomical characteristics and the spatial relationships to its adjacent structures. However, the anatomical features of these structures remain controversial. The controversy focuses on the origination and termination of the fundiform ligament. There are 2 points of view regarding the origination of the fundiform ligament: either it starts from the linea alba, or it is a continuation of Scarpa's fascia [10–12]. It is also unclear whether it attaches to the deep fascia of the penis (Buck's fascia) or attaches to the tunica albuginea [11,13]. Similarly, the origination and termination of the suspensory ligament are under debate [11,14,15]. These uncertainties cause confusion regarding the relationships between the suspensory ligamentous system and its adjacent structures, leading to difficulties in understanding its morphological features and the suspensory mechanism of the penis.

Furthermore, limited by image definition and contrast, with the traditional two-dimensional images, such as those derived from computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound scans, it is difficult to distinguish the penile ligaments [16,17]. Even a 3D digital model built from thin-section MRI images cannot satisfactorily show the detailed anatomical features of these ligaments and surrounding structures [18,19]. Moreover, cadaver dissection and intraoperative observation may destroy the anatomical structures of the penis and relationships to the adjacent structures during

the dissection process. Therefore, those traditional methods cannot accurately reflect the adjacent relationships between the penile suspensory ligamentous system and its adjacent structures. In contrast, the thin-slice cross-sectional images deprived from Visible Human data sets are preferable to the traditional two-dimensional images due to the high resolution, thinner image thickness, and presence of actual anatomical color. The images based on these data sets have an advantage in identifying and outlining the subtle structures without any deformation and loss, such as muscles, fascia, and ligaments [20–23].

In the present study, we set out to identify and outline the anatomical structures of the penile suspensory ligamentous system and its adjacent structures based on the Chinese and American Visible Human data sets and to reconstruct three-dimensional representations of the penile ligaments and related structures. Using this method, we seek to provide a novel tool for surgeons to understand and master the anatomical structures involved in penis-lengthening surgery and the suspensory mechanism of the penis.

Material and Methods

Ethics statement

This study was approved by the Ethics Review Board of the Third Military Medical University. The first Chinese Visible Human (CVH-1), third Chinese Visible Human (CVH-3), and Visible Human Male (VHM) data sets were obtained from voluntary donations. All specimens were adult males and no specimen had any organic diseases or lesions. Informed consent was obtained from the relatives of the participants in the CVH-1 and CVH-3 data sets. The use of the VHM data set was authorized by the U.S. National Library of Medicine (NLM).

Image collection

Successive cross-sectional images, from the lower abdomen to the bottom of the testes, were obtained from the CVH-1, CVH-3, and VHM data sets. Each cross-sectional image was captured using a digital camera. All the images were saved in PNG format. Detailed parameters of these data sets are presented in Table 1.

Image segmentation

The above cross-sectional images were imported into Amira software 5.2.2 (Mercury System Inc., Chelmsford, MA, USA). The corresponding coronal and sagittal images were obtained by changing the orientation of the x, y, and z axes in the coordinate system of Amira software. The suspensory ligamentous

Table 1. Detailed parameters of the CVH-1, CVH-3, and VHM data sets.

	CVH-1	CVH-3	VHM
Sex	Male	Male	Male
Height (cm)	170	182	186
Age (years)	35	21	38
Weight (kg)	65	66	90
Slice thickness (mm)	1	1	1
Total number (slices)	193	151	167
Image resolution	3072×2048	4064×2704	2048×1216

system and its related structures were segmented on the successive cross-sectional images with the segmentation editor provided by Amira5.2.2. In this process, structures with obvious boundaries were segmented semi-automatically, and structures with less obvious boundaries, such as the fundiform ligament, were segmented manually with the magic lasso tool provided by Amira software. The criteria for segmentation were the presence of fibrous tissue fascia and differences in tissue architecture and color.

Three-dimensional reconstruction based on the CVH-1, CVH-3, and VHM data sets

After the segmentation, we reconstructed three 3D models of the above segmented structures from the CVH-1, CVH-3, and VHM data sets in the Amira software. This method of reconstruction was based on a surface-rendering reconstruction. The resulting surface models were smoothed with the Amira software.

The MRI image acquisition

Four male volunteers (mean age 32.2 years; range 28–36) were recruited to undergo MRI scans using a 3.0T system (Magnetom Tim Trio, Siemens Medical Solutions, Erlangen, Germany). The volunteers were healthy and had not undergone previous penile surgery. Informed consent was obtained from all individual volunteers before the MRI scans. The volunteers were imaged from the lower abdomen to the bottom of the testes in a supine position. T1-weighted fast-spin echo sequence images were obtained with the following detailed parameters: repetition time 240 ms; echo time 2.6 ms; field of view 100 cm; pixel size 0.82×0.82 mm; image resolution 512×512; slice thickness 2 mm and spacing 2.2 mm. In total, transverse, coronal, and sagittal MRI images of the anatomical structures of the suspensory ligamentous system and its related structures were obtained and saved as digital imaging and communications in medicine (DICOM) files.

Results

In total, we constructed three 3D surface models of the suspensory ligamentous system and its related structures, including the skin of the penis, superficial fascia of the penis (Colles’ fascia), deep fascia of the penis (Buck’s fascia), tunica albuginea, corpora cavernosa, corpus spongiosum, fundiform ligament, suspensory ligament, arcuate pubic ligament, pubis symphysis, lower rectus abdominis, pubis, and ischio-cavernosus muscles. All identified structures in the VHM data set were represented in 3D reconstruction that could be used for stereoscopic inspection of the details of the structures of interest separately or in self-chosen combinations.

Architecture of the fundiform ligament

On the cross-sectional MRI images, the fundiform ligament was difficult to identify from the surrounding adipose tissues (Figure 1A, 1B). However, on the coronal MRI images, the fundiform ligament was seen to split 2 high-signal-intensity bundles that encased the corpora cavernosa and corpus spongiosum (Figure 2A). Laterally, its fibers had an oblique and longitudinal orientation (Figure 3B). In the case of Visible Human data sets, the fundiform ligament was a fibro-fatty structure with color remarkably similar to that of the surrounding adipose tissues, but its architecture was significantly different from that of the adipose tissues (Figure 1E, 1F). This ligament was adherent to the posterior surface of the superficial fascia of the abdomen and bordered the linea alba posterosuperiorly (Figure 1E). Anteriorly, the fundiform ligament bordered the subcutaneous adipose tissue of the lower abdominal wall (Figure 1E). Posteriorly, it faced towards the rectus abdominis and suspensory ligament (Figure 3A). On the cross-sectional images, the fundiform ligament was divided into left and right bundles during its approach to the penis (Figure 1F). The 2 bundles subsequently fanned out, stretching downward along the corpora cavernosa (Figure 3A). At the level of the lateral side of corpora cavernosa, the 2 bundles merged into the bilateral deep fascia of the penis (Figure 2E).

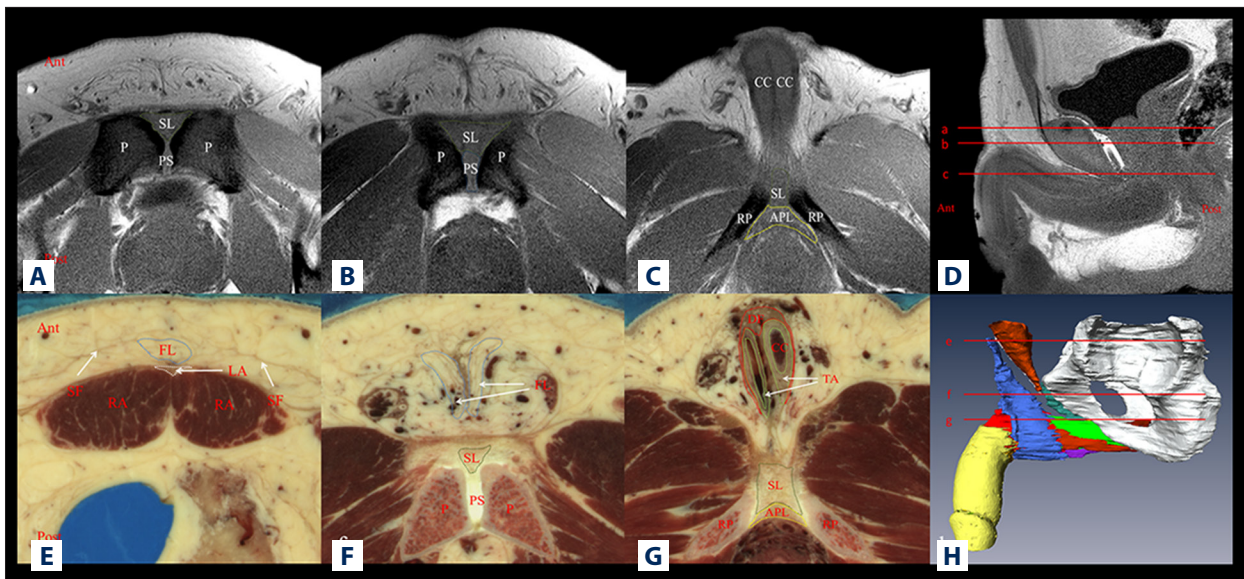


Figure 1. Cross-sectional images of the suspensory ligamentous system and its adjacent structures on the VHM and MRI images. (D) Positions of the transverse sections of panel A–C. Sections show the medium-signal-intensity suspensory ligament (A, B) and arcuate pubic ligament (C) on the MRI images. (H) Positions of the transverse sections of panel E–G. Sections show the position of the fundiform ligament (A, B), suspensory ligament (B), and arcuate pubic ligament (C) in VHM data set. SF – Scarpa’s fascia; FL – fundiform ligament; LA – linea alba; RA – rectus abdominis; SL – suspensory ligament; PS – pubic symphysis; P – pubis; DF – deep fascia of the penis; CC – corpora cavernosa; TA – tunica albuginea; APL – arcuate pubic ligament; RP – ramus of pubis.

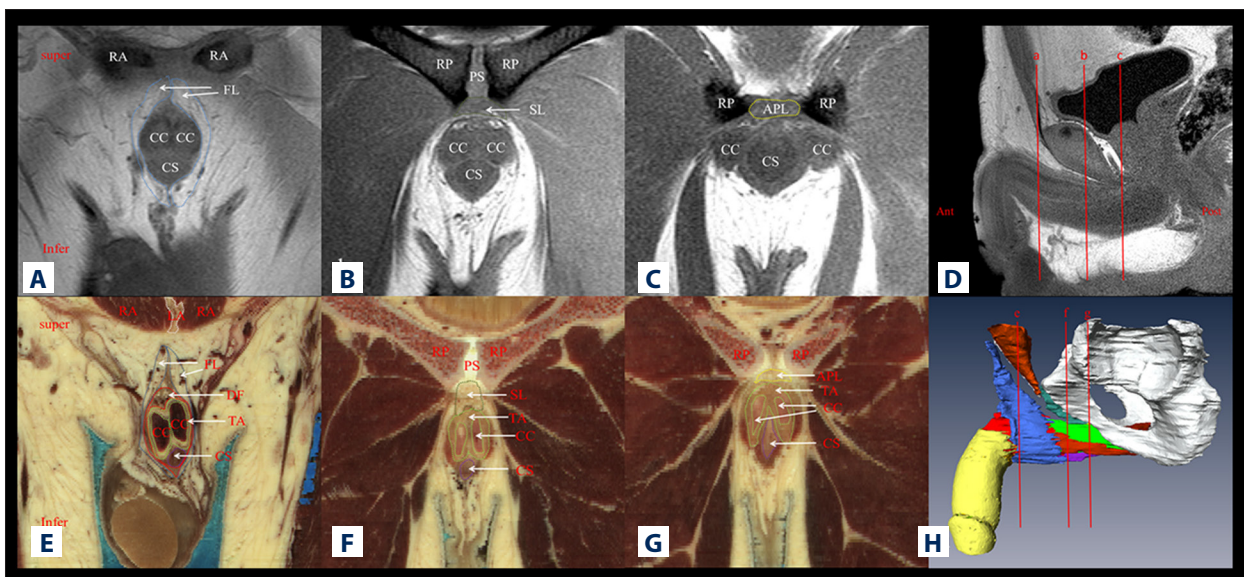


Figure 2. Coronal section of the suspensory ligamentous system and its adjacent structures from the front on the VHM and MRI images. (D) Positions of the coronal sections of panel A–C. Sections show the 2 high-signal intensity bundles of the fundiform ligament (A), the medium-signal intensity suspensory ligament (B) and the medium-signal intensity arcuate pubic ligament (C) on MRI images. (H) Positions of the coronal sections of panel E–G. Sections show the 2 bundles of the fundiform ligament (E), the suspensory ligament (F), and the arcuate pubic ligament (G) in VHM data set. FL – fundiform ligament; LA – linea alba; RA – rectus abdominis; SL – suspensory ligament; PS – pubic symphysis; P – pubis; DF – deep fascia of the penis; CC – corpora cavernosa; CS – corpus spongiosum; TA – tunica albuginea; APL – arcuate pubic ligament; RP – ramus of pubis.

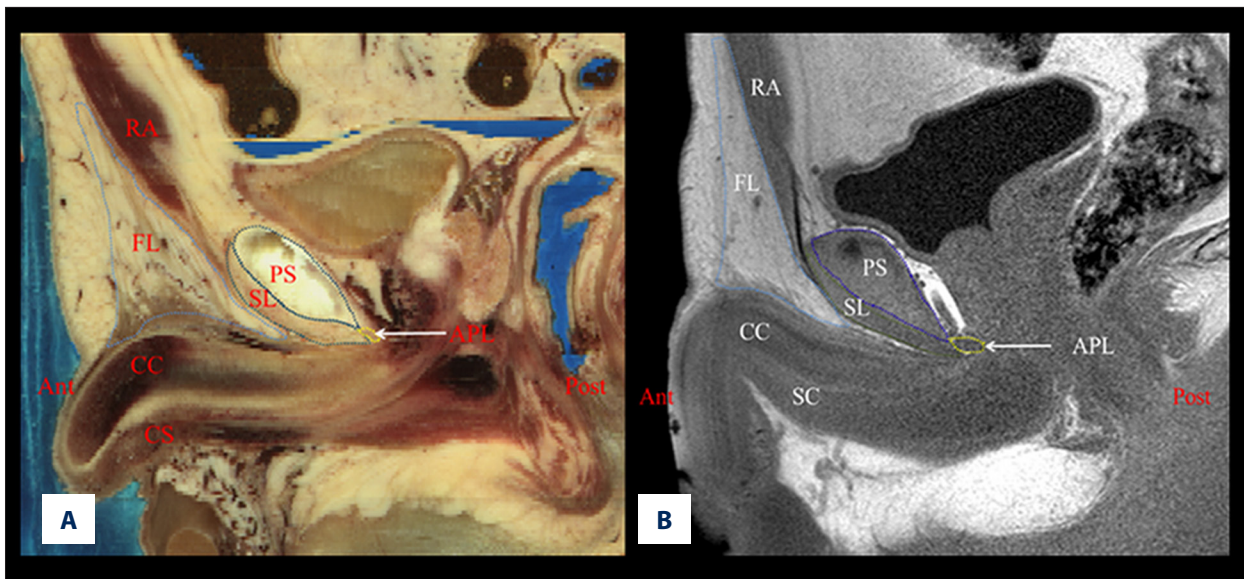


Figure 3. Mid-sagittal section of the suspensory ligament and its related structures on the VHM and MRI images. **(A)** Mid-sagittal section of the suspensory ligamentous system and its related structures in the VHM data set. **(B)** Mid-sagittal section MRI image of the suspensory ligamentous system and its related structures. FL – fundiform ligament; RA – rectus abdominis; SL – suspensory ligament; PS – pubic symphysis; CC – corpora cavernosa; CS – corpus spongiosum; TA – tunica albuginea; APL – arcuate pubic ligament.

Inferiorly, the 2 bundles came together at the bottom of the corpus spongiosum to form the superior part of scrotal septum (Figure 2E). Three-dimensionally, the fundiform ligament was a loop-shaped structure with a narrow upper part and wide lower part, enveloping the corpora cavernosa and the corpus spongiosum (Figure 4A, 4D).

Architecture of the suspensory ligament

On the cross-sectional MRI images, the suspensory ligament was a medium-signal intensity structure (Figure 1A, 1B), which was located between the pubis symphysis and the corpora cavernosa (Figure 2B). However, its attachment to the corpora cavernosa could not be identified from these MRI images. On the cross-sectional images of the VHM data set, the suspensory ligament was a dense colored structure and its anterosuperior portion was shaped like an inverted triangular (Figure 1F). At the base of this ligament, it adhered to the arcuate pubic ligament posteriorly (Figure 1G). The superior margin of this ligament corresponded to the upper border of the pubic symphysis and its posterior margin attached to the anteroinferior surface of the pubic symphysis (Figure 3A). As shown on the coronal images, it attached the tunica albuginea of the corpora cavernosa inferiorly (Figure 2F). As shown in the 3D models, it was a band-shaped structure that extended from the pubic symphysis to the posterior part of the corpora cavernosa, attaching to the tunica albuginea of the corpora cavernosa (Figure 4B, 4D).

Architecture of the arcuate pubic ligament

On the transverse and coronal MRI images, the arcuate pubic ligament was a medium-signal intensity structure (Figures 1C, 2C). Although we identified this structure in the MRI image, its architecture was not well visualized. On the cross-sectional images of the VHM data sets, there was a distinct boundary between the suspensory ligament and arcuate pubic ligament, which allowed us to distinguish these 2 ligaments. The arcuate pubic ligament was a dense colored structure located behind the suspensory ligament (Figure 1G). On the coronal images of the VHM data set, the arcuate pubic ligament was located between the inferior rami of pubis and the tunica albuginea of the corpora cavernosa (Figure 2G). It attached to the posteroinferior border of the pubic symphysis superiorly and adhered to the posteroinferior border of the suspensory ligament anteriorly (Figure 3A). In the posterior view of the 3D model, the arcuate pubic ligament was a crescent-shaped structure which attached to the inferior rami of the pubis laterally (Figure 4C). Inferiorly, it attached to the tunica albuginea of the corpora cavernosa (Figure 4C, 4D).

Discussion

We studied the normal anatomical structures of the suspensory ligamentous system in Visible Human data sets and MRI images. Although the number of specimens was small, the complete procedure was labor-intensive and time-consuming.

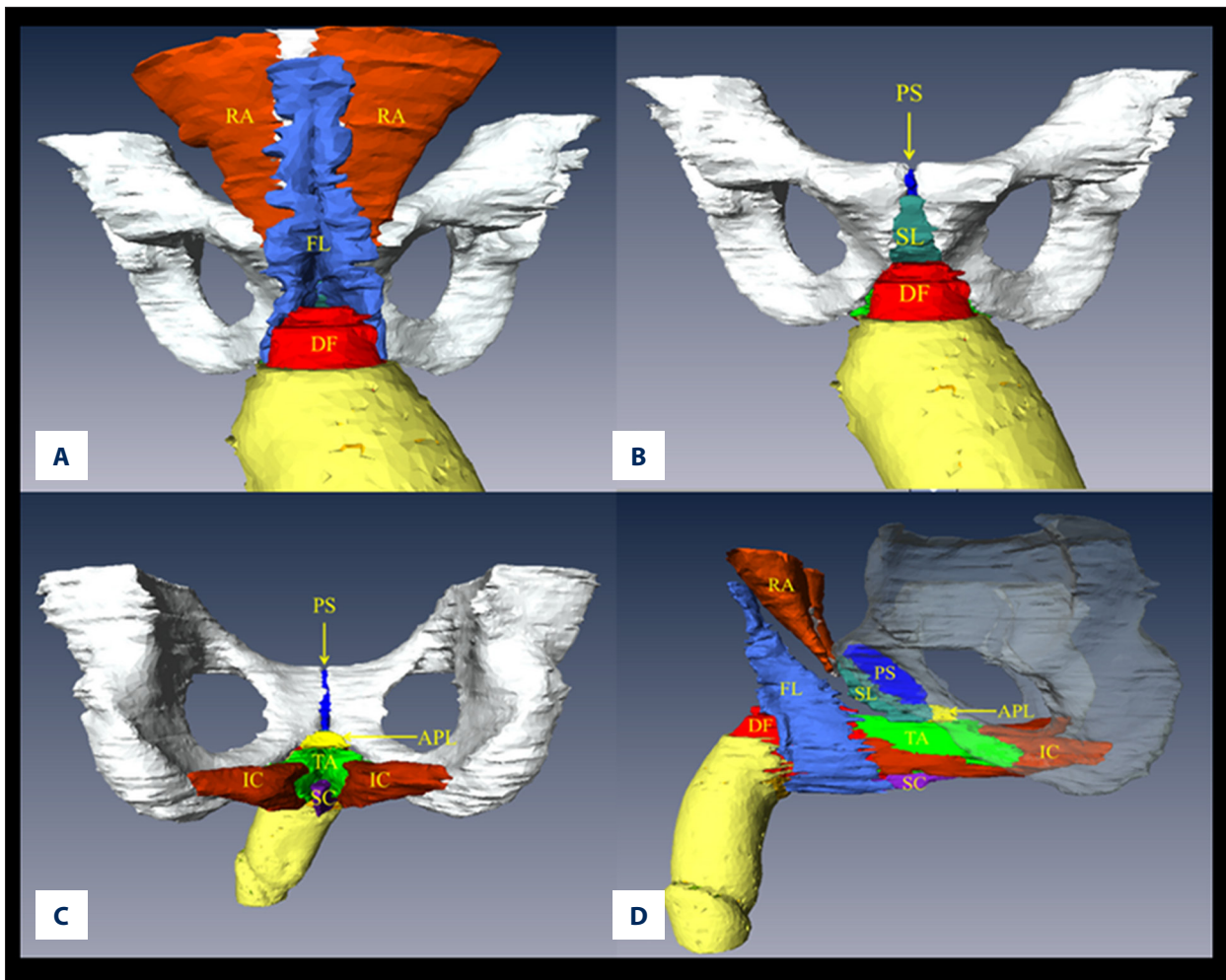


Figure 4. Visualization of the suspensory ligamentous system and its related structures based on the VHM data set. (A) Anterior view of the 3D model. (B) The anterior view of the 3D model with removing of the fundiform ligament, linea alba and rectus abdominis. (C) Posterior view of the 3D model. (D) Left lateral view of the 3D model with transparency of the pelvic bone. FL – fundiform ligament; LA – linea alba; RA – rectus abdominis; SL – suspensory ligament; PS – pubic symphysis; DF – deep fascia of the penis; CC – corpora cavernosa; TA – tunica albuginea; APL – arcuate pubic ligament; IC – ischio cavernosus muscle.

Using this serial-section approach, the shape, location, start-stop point, course, attachment, and adjacent relationships of the penile ligamentous system were presented in the Visible Human data sets and 3D models. Our results identified 3 (superficial, medial, and deep) portions of the penile ligamentous system, corresponding to the fundiform ligament, suspensory ligament, and arcuate pubic ligament, respectively.

First of all, the fundiform ligament was referred to as the superficial fibers of the suspensory ligament and a continuation of the lower part of the Scarpa's fascia [10]. Liu et al. agreed that the fundiform ligament extended from the Scarpa's fascia of the abdomen to the penile shaft [12]. However, in 1998, Hoznek et al. identified the fundiform ligament as the continuation of the linea alba [11]. Protergerou et al. also supported

Hoznek's view by analyzing cadavers [9]. In the present study, combining the transverse, sagittal, and coronal images of the CVH and VHM data sets, we found that the fundiform ligament originated from the deep layer of the superficial fascia of the abdomen (Scarpa's fascia). It was a superficial, loose, fibro-fatty tissue behind the lower part of the abdominal wall, without a direct connection to the linea alba. According to Hoznek et al., the 2 bundles extended laterally and continued with the scrotal septum inferiorly [11]. In the present study, we confirmed that the inferior margin of the fundiform ligament was the anterosuperior part of the scrotal septum, which was in accordance with Hoznek's research.

According to our observation, the fundiform ligament is independent of the other penile ligaments. Its role is to support

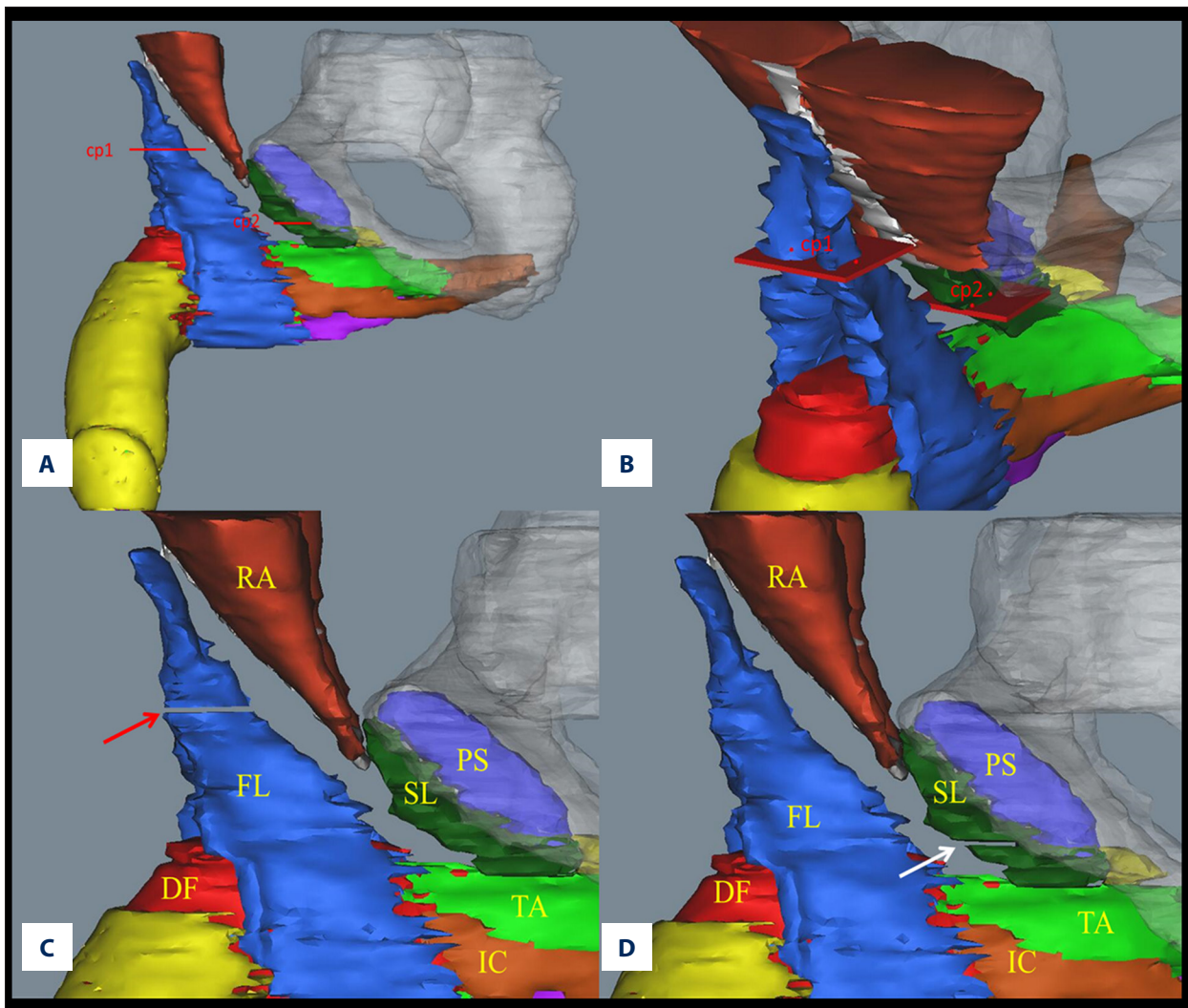


Figure 5. 3D illustration of the dissection of the penile ligaments. (A) Left lateral view of the cut plane of the penile ligaments; (B) the isometric view of the cut plane of the penile ligaments; (C) the fundiform ligament is completely dissected at the level of the superior border of the pubic symphysis (the red arrow); and (D) the suspensory ligament is partially dissected (white arrow). Depth of incision reaches the anteroinferior border of pubic arch. cp1 – the cut plane of the fundiform ligament; cp2 – the cut plane of the suspensory ligament; FL – fundiform ligament; RA – rectus abdominis; SL – suspensory ligament; PS – pubic symphysis; DF – deep fasica of the penis; TA – tunica albuginea; IC – ischiocavernosus muscle.

the pendulous part of the penis in front of the pubis. However, it has no direct connection with the pubic symphysis and the tunica albuginea of the corpora cavernosa, which means that its connection to the penis is not tight and its penile suspensory function is not significant during penile erection. Hoznek et al. suggested that it did not have any support role for the penis [11]. As a consequence, a complete dissection of this ligament in penis-lengthening surgery may have little influence on the stability of the penis. In addition, we noticed that the dorsal deep arteries, veins, and nerves of penis passed through the 2 bundles of the fundiform ligament. To avoid injury to these important structures, the cut plane should be parallel to the superior border of the pubic

symphysis where the fundiform ligament starts to divide into 2 bundles (Figure 5A–5C).

Regarding the suspensory ligament, some authors proposed that it originates from the pubic symphysis [11,14]. Wang et al. and Liu et al. confirmed this view by reconstructing 3D models based on thin-slice MRI images [24,25]. However, Hsieh et al. argued that the suspensory ligament was an extension of the linea alba [15]. In our study, we observed that the suspensory ligament was located behind the rectus abdominis, and its entire posterior margin was attached to the inferior surface of the pubic symphysis, which indicates that this ligament originated from the pubic symphysis instead of

the linea alba. Furthermore, the controversial issue regarding the suspensory ligament's attachment to the penis remains unclear. Some authors demonstrated that it attaches to Buck's fascia inferiorly [13,14]. However, Hoznek et al. and Li et al. proposed that it ended by attachment to the tunica albuginea of the corpora cavernosa [1,11]. With the aid of high resolution and more detailed anatomical features provided by the CVH-1, CVH-3, and VHM data sets, we found that Buck's fascia gradually vanished during its extension to the posterior part of the corpora cavernosa, and the suspensory ligament directly attached to the tunica albuginea of the corpora cavernosa.

On the other hand, the suspensory ligament is a deep, dense, fibrous connective tissue that suspends the posterior segment of the corpora cavernosa to the inferior border of the pubic symphysis, connecting the pubic symphysis to the tunica albuginea of the corpora cavernosa. Depending on the attachment to the pubic symphysis and tunica albuginea, the suspensory ligament behaves as a major suspensory apparatus for the penis in erection. When the penis is erect, the suspensory ligament stretches tight under traction by the tunica albuginea and firmly fixes the corpora cavernosa to the pubic symphysis, stabilizing the penis at the specific angle required for vaginal penetration and sexual intercourse. In clinical practice, most authors prefer to incise the suspensory ligament to increase penile length [1-3,7,8]. However, complete dissection of this ligament may result in penile instability and deformity, as well as a variable degree of erectile dysfunction [1]. Protogerou et al. also cautioned that extensive dissection of the suspensory ligament may cause the penis to lose its stability and perhaps lose its upward orientation during an erection [9]; they suggested that the incision should stop before reaching the inferior border of the pubic arch to avoid postoperative penile instability and erectile dysfunction. According to the topography of the suspensory ligament, this ligament depends mostly on its posteroinferior portion to connect the penis to the pubic symphysis. We believe that incising the superficial part of the suspensory ligament while preserving the deep part can still maintain the suspensory function of this ligament. Therefore, a partial incision of the suspensory ligament to increase penile length may have slight influence on the stability of the penis, but the incision plane should be close to the anteroinferior border of the pubic symphysis and away from the dorsal aspect of the penis to avoid injury of the dorsal deep arteries, veins, and nerves of the penis (Figure 5A, 5B). To preserve the deep part of this ligament, the depth of the incision should not be beyond the anteroinferior border of the pubic arch (Figure 5D)

There are few studies on the precise anatomical features of the arcuate pubic ligament. This ligament lies in a deeper position compared to the other penile ligament, and is seldom touched in penis-lengthening surgery. As shown in the 3D model, the

arcuate pubic ligament attaches the corpora cavernosa to the pubis symphysis, so it has similar function to the suspensory ligament. Below it, the corpora cavernosa divides into 2 crura corpora cavernosa, which attach to the inferior rami of the pubis. Each crux is covered by the ischiocavernosus muscle. The arcuate pubic ligament, along with the crura corpora cavernosa and ischiocavernosus muscles, firmly attach the corpora cavernosa to the pubis and ischium, constituting the fixed apparatus of the penis. Furthermore, Steiner suggested that the arcuate pubic ligament may be involved in composing the urethral suspensory mechanism [26].

In summary, the identification and visualization of the penile suspensory ligamentous system can greatly facilitate the biological modeling of physical and physiological information of the penis and its related structures. The presented 3D reconstruction model can be used by surgeons to carry out noninvasive examination, preoperative planning, virtual dissection, and postoperative evaluation of penis-lengthening surgery, contributing to the improvement of the accuracy of the diagnosis and reliability of the operation. Furthermore, using the biomechanical methods, this 3D model can be potentially applied to the development of a 3D biomechanical model to predict stress, strain, and deformation of the penile suspensory ligaments and its related structures after penis-lengthening surgery. In a future study, we plan to translate this 3D model into a finite element model (FEM) to quantitatively analyze the influence of dissecting different penile suspensory ligaments on the stability of the penis.

Our study has certain limitations. First, the number of study samples, both in the Visible Human data set and MRI images, was relatively small. Second, some slim vessels, nerves, and fascia, such as the superficial dorsal veins of the penis and deep dorsal arteries and nerves of the penis, were not well demonstrated. Although we identified these structures, the entire architectures were difficult to trace and segment.

Conclusions

We presented a detailed anatomical description and illustration of the penile suspensory ligamentous system via a 3D visualization of the Visible Human data sets. Using this technique, the controversy regarding the suspensory ligamentous system has been clarified and defined. Moreover, the 3D models based on the Visible Human data sets provide a foundation for the urological and plastic surgeons to familiarize and master the suspensory mechanism of the penis, thereby contributing to the improvement of penis-lengthening surgery.

Acknowledgements

The CVH-1 and CVH-3 data sets and the Amira software 5.22 were provided by the Institute of Digital Medicine, College of Biomedical Engineering of the Third Military Medical University. The VHM data set was provided by the National Institutes of Health, the U.S. National Library of Medicine.

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Conflict of interest

The authors have no conflict of interest to declare in regard to this work.