Sectional Anatomy and Three-Dimensional Visualization of the Posterolateral Complex of the Knee Joint Based on Undeformed High-Resolution Sectional Anatomical Images

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ABSTRACT
The anatomy of the posterolateral complex (PLC) of the knee is usually studied by dissection and magnetic resonance (MR) imaging, which is still controversial. We aim to study it based on the images and an interactive 3D-PDF from the Chinese Visible Human (CVH) datasets. CVH datasets (six transverse and one coronal) of the PLC and its adjacent structures were segmented and three-dimensionally reconstructed. Histological sections images were used to establish criteria for the segmentation. MR images were studied in comparison with CVH images. The PLC was mainly composed of the fibular collateral ligament (FCL), popliteofibular ligament (PFL), arcuate popliteal ligament (APL), popliteus tendon (PT), fabellotibial ligament (FFL) and biceps femoris tendon (BT). These structures had origins or insertions located close to each other and collectively maintained the stability of the PLC. The origins of the PT and the FCL were located on the lateral condyle of the femur. The APL was “Y” shaped and had a 100% occurrence in our study. Its lateral and medial heads originated, respectively, from the posterolateral part and medial-inferior part of fibrous capsule close to the lateral femoral condyle. The FCL, BT, main trunk of the APL, PFL and FFL had adjacent insertions on the posterolateral fibular head.

Grant sponsor: Military Youth Science Foundation of China; Grant number: No. 16QNP100; Grant sponsor: National Key Research and Development Program of China; Grant number: No. 2016YFC0106402; Grant sponsor: National Nature Science Foundation of China; Grant number: No. 81772330 and No. 31771324; Grant sponsor: Higher Education Teaching Reform Research Project of China Chongqing; Grant number: 153222.

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Received 11 October 2017; Revised 30 January 2018; Accepted 5 March 2018.
DOI: 10.1002/ar.23926
Published online 29 October 2018 in Wiley Online Library (wileyonlinelibrary.com).

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POSTEROLATERAL COMPLEX OF THE KNEE JOINT

CVH high-resolution sectional anatomical images and a 3D-pdf provided detailed morphological data for the PLC, and improved the identification and diagnostic accuracy for the PLC in MRI. We speculate that APL has a strong biological and mechanistic significance in the PLC. Anat Rec, 301:1764–1773, 2018. © 2018 Wiley Periodicals, Inc.

Key words: Chinese visible human; knee joint; posterolateral complex; sectional anatomy; visualization

The posterolateral complex (PLC), also known as the posterolateral corner (PLC) (Krudwig et al., 2002; Vinson et al., 2008; Devitt and Whelan, 2015; Rosas, 2016), is a complicated anatomical and functional complex located in the posterolateral region of the knee. The PLC consists of multiple tendons and ligaments that maintain the static and dynamic stability of the posterolateral structure of the knee.

PLC injuries are mainly caused by sports injuries and traffic accidents, resulting in knee varus, tibial external rotation and knee flexion deformity. The cruciate ligaments function to restrain the human knee joint to prevent hyperextension and hyperflexion (Fuss, 1991). During cruciate ligaments injury, the stress on the knee joint is often concentrated in the posterolateral part of the knee, which can cause intense strain that can damage the PLC. Neglecting PLC damage during surgery to reconstruct the cruciate ligaments can lead to postoperative knee joint instability, pain, articular cartilage degeneration and failed cruciate ligament reconstruction (Noyes and Barber-Westin, 2005; Bonanzinga et al., 2015; Lee et al., 2015). Early diagnosis and treatment of PLC injury is critical to the recovery of knee function; therefore, many anatomists and orthopedists have focused on the anatomy, biomechanics and surgical reconstruction of the PLC (Seebacher et al., 1982; Collins et al., 2015; Devitt and Whelan, 2015; Rosas, 2016).

However, most of the existing findings regarding the PLC are based on dissection and magnetic resonance imaging (MRI). Dissection causes destruction of the normal structure, and MRI provides low-resolution grayscale color-mode images; therefore, these images do not precisely reflect the composition, 3D morphology and spatial relationships of the PLC.

The Chinese visible human (CVH) frozen anatomical image datasets include high-definition, high-resolution, thin-section images that represent normal Chinese people of average size with no organic diseases (Zhang et al., 2004; Zhang et al., 2005, 2006; Wu et al., 2012). Therefore, we aimed to use CVH datasets to study the anatomy of the PLC. We also used images of histological sections of knees from Utrecht University as comparative criteria for structural segmentation, and MR images were studied and compared with CVH images. Compared to the other images, CVH images can better show the precise composition, 3D morphology and spatial relationships of the PLC, improving the identification and diagnostic accuracy for the PLC in MRI.

MATERIALS AND METHODS

Data Acquisition

We selected 7 CVH knee datasets, including 6 sets of transverse section images of CVH-1, CVH-2, and CVH-5 of the bilateral knee and one set of coronal section images of Knee-1. (Zhang et al., 2004; Zhang et al., 2005, 2006)

All cadavers were enrolled in the body donation program of the Chinese Visible Human project. The study was approved by the Ethics Committee of Third Military Medical University (Chongqing, China). Written informed consent was obtained from the donors or their family members. The image layer thickness ranged from 0.2 to 1.0 mm, the maximum resolution was 4,064 × 2,704, and the size of each pixel was 0.12 × 0.12 mm²; the basic parameters of the CVH specimens are shown in Table 1.

We selected sagittal histological images of a knee from Utrecht University, The Netherlands. These images came from tissue sections obtained using a Leica CM3600 macrotome that were Mallory–Cason stained. The section thickness was 25 µm, the resolution was 2,288 × 3,011, and the size of each pixel was 50 × 50 µm². The study was approved by the Ethics Committee of Utrecht University, The Netherlands.

We also selected MR images from the Southwest Hospital, which is affiliated with the Third Military Medical University, China. Informed consent was obtained from patients and their family members, and approval was obtained from the Institutional Review Board of the Third Military Medical University. The parameters used for the transverse and coronal knee images were as follows: TSE T1WI imaging, imaging matrix 320 × 240, repetition time (TR) ms/echo time (TE) ms = 500/12, field of view (FOV) = 130 mm, slice thickness = 3 mm.

PLC Image Segmentation

The CVH datasets were imported into Amira 5.2.2 commercial software (https://www.fei.com/software/amira-3d-for-life-sciences/; the Amira segmentation interface is shown in Fig. 1). The PLC and its adjacent structures were identified and segmented based on the natural color differences in the images of the fascial septa between the knee structures. At the same time, we used the sagittal histological images of the knee from Utrecht University as comparative criteria (Fig. 2A,B) for segmentation. The images were stained with Mallory–Cason stain and showed the details of the muscle tissue and collagen-based tissues, including tendons, fascia and ligaments,
which can facilitate structural identification (van Leeuwen et al., 1990).

The segmented PLC structures included the popliteus tendon (PT), the fibular collateral ligament (FCL), the popliteofibular ligament (PFL), the biceps femoris tendon (BT), the arcuate popliteal ligament (APL) and the fabellofibular ligament (FFL). We also segmented the adjacent structures, including the femur, tibia, fibula, biceps femoris, patella, patellar ligament, gastrocnemius, soleus, popliteal muscle, tibial cartilage, femoral cartilage, fibula cartilage, patellar cartilage, arteries, veins, nerves, lateral meniscus, knee joint cavity, anterior cruciate ligament, posterior cruciate ligament, medial meniscus, oblique popliteal ligament, iliotibial tract (IL), posterior meniscofemoral ligament, lateral meniscus, medial meniscus, transverse ligament of knee, fabella, and knee joint capsule.

3D Reconstruction

Using Amira software, after the data segmentation was completed, the PLC and its adjacent structures underwent 3D reconstruction, and the model surface was smoothed and simplified. Finally, the interactive 3D-PDF model was created with CINEMA 4D (Maxon Computer

TABLE 1. Basic information and detailed parameters of CVH

<table>
<thead>
<tr>
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<th>CVH-1</th>
<th>CVH-2</th>
<th>CVH-5</th>
<th>Knee-1</th>
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<tr>
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<td>25</td>
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<tr>
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</tr>
<tr>
<td>Weight (kg)</td>
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<td>54</td>
<td>59</td>
<td></td>
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<td>Section direction</td>
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<td>Transverse section</td>
<td>Coronal plane</td>
</tr>
<tr>
<td>Section thickness (mm)</td>
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<td>0.25,0.5</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Resolution</td>
<td>3,072 × 2048</td>
<td>3,072 × 2048</td>
<td>4,064 × 2,704</td>
<td>4,082 × 2,718</td>
</tr>
</tbody>
</table>

Fig. 1. Amira software interface.
Because these structures had adjacent origins or insertions, we believe that they act in conjunction to maintain PLC stability and are the primary structures that make up the PLC (Fig. 4).

**Popliteus Tendon**

The PT is the most medial structure of the PLC, and if was found to originate on the posterolateral side of the lateral femoral condyle. It originated inside the knee joint capsule and ran obliquely from the bottom of the popliteal fossa and toward the posteromedial side of the knee joint cavity, passed through the posterior fibrous capsule of the knee, divided into the medial bundle and lateral bundle at the popliteal fossa and inserted separately in the popliteal muscle (Figs. 4A–D, 5A–J, 6A–H, and 7A). The length of the popliteal tendon trunk was 31.39 ± 6.11 mm, the width of the trunk was 5.31 ± 0.49 mm, the length of the lateral bundle was 16.21 ± 4.02 mm, and the length of the medial bundle was 15.76 ± 4.46 mm. The PT appeared dark red in the CVH images (Figs. 5A–D and 6A–D), and it had a low signal intensity and clear boundaries in the MR images (Figs. 5E–G and 6E–G).

**Popliteofibular Ligament**

The PFL originated in the middle PT or the posterolateral articular fibrous capsule of the lateral femoral condyle behind the knee joint capsule, ran in a posterolateral direction to the posteromedial APL, and ended at the apex of the fibular head. The length of the PFL was 18.55 ± 4.01 mm, its width was 2.44 ± 0.62 mm, and its thickness was 1.68 ± 0.11 mm (Figs. 4C,D, 5D,G–J, 6D, H, and 7B). The PFL was elliptic in the CVH transverse tomographic images (Fig. 6D). In the coronal plane, it appeared as a narrow stripe and ran obliquely between the lateral PT and the fibular head, which was located in the posterior region of the knee joint and inside the BT and APL (Fig. 5D). The PFL appeared dark red on the CVH images, which was similar to the color of the IL and the FCL. The ligament was difficult to accurately identify on the transverse MR images, which showed a low signal intensity and the same shape in the CVH coronal image as in the MR coronal image (Fig. 5G).

**Arcuate Popliteal Ligament**

The APL appeared as an asymmetric “Y” shape and had a wide trunk. The lateral head was thicker and longer, with a length of 18.11 ± 3.05 mm and a width of 10.10 ± 2.29 mm. It started from the fibrous capsule of the knee, close to the posterolateral side of the lateral femoral condyle and ran caudally close along the joint capsule. The medial head was shorter, with a length of 12.83 ± 1.4 mm and a width of 4.37 ± 0.9 mm. It started from the fibrous capsule of the knee, close to the medial-inferior part of the lateral femoral condyle, ran in a lateral and caudal direction and fused with the lateral head, where it formed the trunk with the lateral head. The trunk ran between the medial PFL, the anterolateral FCL and posterolateral BT in a caudal direction in the lateral region of the knee joint capsule. It ended at the fibular head, with a length of 14.27 ± 3.98 mm and a width of 9 ± 1.27 mm; the angle between the medial and lateral heads was 74.12 ± 7.09° (Figs. 5B,C,F–H, 6A,B, D,F, H, and 7C). The APL appeared gray in the CVH
images and was irregular in shape (Fig. 6A–D). In the MR images, it could not be continuously identified and distinguished from the adjacent high signal intensities of the joint capsule and fat.

**Fibular Collateral Ligament**

The FCL started from the lateral epicondyle of the femur, and originated close behind the upper and posterolateral side of the origin of PT. The FCL passed through and ran caudally along the lateral knee capsule and inserted at the lateral edge of the fibular head, with a length of $42.12 \pm 8.67$ mm, a width of $4.15 \pm 0.16$ mm, and a thickness of $2.58 \pm 0.24$ mm (Figs. 4B, 5A,B,E,H,I, 6A–G,I, and 7D). The FCL had a regular elliptical structure on the CVH transverse images, appeared long and narrow on the CVH coronal images, and appeared dark red (Fig. 5A,B, 6A–D). The FCL had a low signal intensity, and the boundary was clear in the MR images. (Fig. 5E, 6E,F).

**Biceps Femoris Tendon**

The BT is the most lateral structure of the PLC, originating from the biceps femoris, vertically extending caudally along the lateral aspect of the APL, and ending at the lateral margin of the fibular head. Its length was $69.07 \pm 10.94$ mm, and its width was $8.37 \pm 1.69$ mm (Figs. 4B–D, 5D,F–J, 6A–H, and 7E). The BT appeared dark red on the CVH images (Fig. 6A–D); it was narrow and long and was located between the biceps femoris and fibular head and lateral of the APL in the CVH coronal plane images (Fig. 5D). On the MR images, it had a low signal intensity and a clear boundary (Fig. 5F,G, 6E–G).

**Fabellofibular Ligament**

The fabella and FFL were found in 1 CVH specimen. The fabella was round, surrounded by cartilage, and was white. The FFL appeared light red, started from the bottom of the fabella, extended caudally along the posterior side of the PLC, and ended above the apex of the fibular
The length of the FFL was 28.27 mm, and the width was 5.28 mm (Fig. 5H,J).

The IL started from the fascia lata, was located on the anterolateral side of the knee, gradually narrowed toward the distal region, and stopped at Gerdy’s tubercle on the lateral region of the tibia (Figs. 4A–D and 6A–H). It appeared dark red in the CVH images (Fig. 6A–D); it had a low signal intensity on the MR images and had a clear boundary (Fig. 6E–G).

**DISCUSSION**

In recent years, the importance of the PLC has been paid much attention by anatomists, orthopedists, and rehabilitation physicians. Many research teams have studied the composition, 3D morphology, structural relationships, and biomechanics of the PLC, usually by dissection or MRI. (Kim et al., 2011; Yoon et al., 2011; Collins et al., 2015; Devitt and Whelan, 2015; Rosas, 2016; Zhang et al., 2016) In this study, the use of cryosectional CVH images ensured that the PLC structure was not displaced or damaged, and they provided true-color, highly precise, high-resolution, and thin-sectional anatomical images, which can show the detailed features of the PLC.

**Anatomy of PLC**

The PLC consists of the FCL, FFL, PT, APL, and PFL, as shown in past studies (Seebacher et al., 1982; Rosas, 2016). Collins et al. advise including the deep posterolateral knee joint capsule (Collins et al., 2015), while Haims et al. think that the IL, BT, mid-third lateral capsular ligament, gastrocnemius tendon, coronal ligament, popliteus meniscus ligament, and popliteus muscle should also be considered as PLC structures (Haims et al., 2003; Harish et al., 2006; Raheem et al., 2007). Vinson et al. believe that the BT and IL play roles in stabilizing the PLC (Vinson et al., 2008). We studied the PLC from CVH datasets (Zhang et al., 2004; Zhang et al., 2005, 2006), histological sectional images and MR images. We found that the PLC was primarily composed of the FCL, PFL, APL, PT, BT, and FFL. Because these structures had highly adjacent origins or insertions and collectively maintained the stability of the PLC, damage to one structure may lead to associated damage in other adjacent structures.

We found that the FCL, BT, and PT were consistently identifiable in the PLC from CVH datasets and MR images, consistent with the results reported by Collins et al. (2015). The IL is located in the anterolateral part of the knee, and its origin and insertion are not close to PLC structures, so it does not belong to the PLC, which is consistent with previous research (Seebacher et al., 1982; Rosas, 2016).

**Arcuate Popliteal Ligament and Fabellofibular Ligament**

The APL is a “Y”-shaped capsular, thickening structure. It can obviously strengthen the posterolateral region of the knee joint (Thaunat et al., 2014). It appears gray in CVH images and has no obvious boundary with the joint capsule, and we speculate that it is mechanically weaker than the dark red, clear-boundary FCL, PFL, and PT. We found that the occurrence of the APL in CVH specimens was 100%, consistent with the results of the gross anatomical methods of Raheem et al. (2007) but inconsistent with the 61.9% occurrence reported by Minowa et al. (2004). The APL has no obvious shallow or deep layers. The shape and location of the APL are still ambiguous in various versions of anatomy atlases and textbooks and in different anatomical studies (Zhang et al., 2004; Zhang et al., 2005, 2006; Raheem et al., 2007; Rosas, 2016). Harish et al. studied the APL based on MR images and believed that the APL receives fibers from the oblique popliteal ligament (Harish et al., 2006). In CVH images, the APL and oblique popliteal ligament are both thickenings of the joint capsule, but they have no significant cross fusion with each other.

In CVH images, we found only 1 occurrence of the FFL. The FFL is located at the posteromedial aspect of the APL medial head, with fat between them. The FFL stabilizes the PLC in combination with the APL. It has also been reported that the FFL and APL closely contact each
other. Their thicknesses were negatively correlated, and a well-developed APL may lead to a thinner FFL or the fusion of the FFL and APL, which will also lead to the boundaries of the FFL and APL being difficult to distinguish (Minowa et al., 2004).

**Biomechanical Characters of the PLC**

The PLC plays a major role in maintaining the stability of the posterolateral knee joint. It has been generally accepted that PLC damage can lead to posterolateral rotatory instability (Hughston et al., 1976; Lee et al., 2015). It is likely that the FCL, PFL and PT are the most important mechanical structures of the PLC (Rosas, 2016).

From our research, the origin and insertion of the FCL are at the same location as the proximal and distal areas of PLC structures. The FCL is relaxed while the knee is flexed and is tensed while the knee is extended, and it plays an important role in preventing knee varus, tibial external rotation and tibial retrusion.

We believe that the PT is one of the main mechanical structures of the PLC. Because the popliteus muscle connects to the PT, it shows great flexibility in effectively inhibiting knee varus instability while bending the knee from 0° to 90° (Nielsen and Helmig, 1986). However, some studies have shown that resection of the PT does not change the static balance of the knee, suggesting that the PT is not the main static stabilizer outside the tibia (Kesman et al., 2011; Thaunat et al., 2014). Some studies propose that reconstruction of the PLC without reconstructing the PT can also achieve stability of the knee (Apsingi et al., 2008; Yoon et al., 2011).

CVH sectional anatomical images showed that the PFL appears dark red, and has a herringbone shape in combining with the PT; it can prevent external rotation of the joint and is very important for stabilizing the posterior lateral region of the knee (Maynard et al., 1996). The PFL is also called the fibular connection of the PT, which links the PT to the fibular head and should not be confused with the APL (Oransky et al., 1989). The occurrence of the PFL was 100% in our study, which is inconsistent with the results of Collins et al., who reported that the
PFL was observed in 19 of 22 cases (Collins et al., 2015). Collins’ study was based on MR images, which have lower resolution and larger spacing than images from CVH datasets and may not allow for a clear recognition of the PFL. In 3D images, the PFL is cylindrical or fan-shaped, which is consistent with other studies (Wadia et al., 2003; Raheem et al., 2007). Seebacher et al. divided the PFL into deep and shallow layers through dissection (McCluskey and Blackburn, 1980; Seebacher et al., 1982; Krudwig et al., 2002), but we speculate that the deep and shallow layers are dissection artifacts.

We think that the APL is also an important biomechanical structure of the PLC. The origin of the lateral head of the APL is located in the proximal region of the PLC, and the insertion of the APL is located the distal region of the PLC. It has been suggested that both the posterior cruciate ligament and the APL play important roles in stabilizing the lateral region of the knee joint. The functional recovery of these ligaments is important for the treatment of lateral ligament injuries (Thaunat et al., 2014).

CONCLUSION

Because CVH images have the advantages of thin layers, high precision and true colors, they can accurately display the specific composition, 3D shape and structural relationships of the PLC. These images can provide detailed morphological data for MRI diagnosis of the knee joint and can help to improve the accuracy of joint structure recognition and diagnosis. From the anatomical structure and interactive 3D-PDF, the FCL, PFL, APL, FFL and PT were found to be located in close proximity in the posterolateral region of the knee, and their origins or insertions are located in proximal or distal areas of the PLC structure. We speculate that the APL has a strong biological and mechanical significance in the PLC.

DISCLOSURE OF INTEREST

The authors declare that they have no conflicts of interest concerning this article.

LITERATURE CITED


