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Evolution of the Ischio-Iliac Lordosis during Natural Growth and Its Relation With the Pelvic Incidence
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Tom P.C. Schlösser, MD1; Michiel M.A. Janssen, MD, PhD1; Tomaž Vrtovec, PhD2; Franjo Pernuš, PhD2; F. Cumhur Öner, MD, PhD1; Max A. Viergever, PhD3; Koen L. Vincken, PhD3; René M. Castelein, MD, PhD1.

From the 1Department of Orthopaedic Surgery, University Medical Center Utrecht, Utrecht, the Netherlands; 2Faculty of Electrical Engineering, University of Ljubljana, Slovenia; 3Image Sciences Institute, University Medical Center Utrecht, Utrecht, the Netherlands. Corresponding author: R.M. Castelein, MD, PhD. E-mail: R.M.Castelein@umcutrecht.nl.

Computerized determination of the ischio-iliac angle from CT images of the pelvis

Introduction
The computerized method for the determination of ischio-iliac angle from computed tomography (CT) images of the pelvis exploits the image intensity appearance of CT images and the anatomical information in the form of the shape of the observed objects of interest (i.e. sacrum, femoral heads, ischium) in three dimensions (3D). The applied algorithms were implemented in the C++ programming language and can be run on any standard personal computer. The method consists of the following parts:
- user initialization,
- computerized determination of the exact centers and size of femoral heads in 3D,
- computerized determination of the exact center and inclination of the sacral endplate in 3D,
- computerized determination of the left and right ischial axis in 3D, and
- computation of the ischio-iliac angle.

User initialization
For a given 3D CT image of the pelvic and lumbar spinal area of the observed subject (at least L5 vertebral body visible), the user manually determined the approximate center of the left femoral head, right femoral head and L5 vertebral body by navigating through sagittal, coronal and axial cross-sections (Fig. 1). In is important to note that these anatomical structures can be easily identified in 3D with basic anatomical knowledge. Moreover, the resulting three points were not required to be at the exact centers of these anatomical structures but served to initialize the computerized method by defining the locations of the volumes of interest (VOIs) in the 3D image.
Fig. 1. The manually defined approximate centers of (a) the left femoral head, (b) the right femoral head and (c) the L5 vertebral body, which served to initialize the computerized method for the determination of ischio-iliac angle, shown in corresponding sagittal (top), coronal (middle) and axial (bottom) CT cross-sections of a selected subject.

**Computerized determination of the exact centers and size of femoral heads in 3D**

The determination of the exact centers and size of the femoral heads in 3D was performed independently for the left and right femoral head. For each femoral head, a VOI of size \(70 \times 70 \times 70\) mm and centered in the corresponding manually defined initialization point (i.e. the approximate center of the femoral head) was first extracted. To determine the exact center of the femoral head, we exploited the geometrical properties of image intensity vectors, which were computed using Sobel gradient operator. Namely, image intensity gradient vectors are orthogonal to the edges in the image, and their magnitude is proportional to the edge strength, i.e. the magnitude is in the case of CT images therefore the largest on the edges of bone structures. At each point in the VOI, a line in the direction of the image intensity gradient vector at that point was constructed. By superimposing the lines obtained from every point, a 3D accumulator image of the VOI was obtained, and its values represented the probabilities where these lines most often intersected. As the femoral head is a relatively spherical structure, lines most often intersected in the geometrical center of the femoral head, which was identified as the location of the maximal value of the 3D accumulator image. Once the center of the femoral head was determined, its size was obtained by finding the best fit sphere that maximized image intensities within the sphere and the magnitude of image intensity gradient vectors on the surface of the sphere (Fig. 2).
Computerized determination of the exact center and inclination of the sacral endplate in 3D

The determination of the exact center and inclination of the sacral endplate in 3D was performed by first extracting a VOI of size 100 × 100 × 100 mm that was centered in the manually defined initialization point (i.e. the approximate center of the L5 vertebral body). Next, the surface of the sacral endplate was identified as the first bone structure below the L5 vertebral body by observing image intensities in the CT image and the corresponding image intensity gradient vectors. From the center of the VOI (i.e. from the initialization point), rays were projected at different angles in the caudal direction, and image intensities were computed along each ray. As, in the case of CT images, the ray with the maximal sum of image intensities is oriented towards the largest bone structure, it was selected to represent the direction of the sacrum. The point on the surface of the sacral endplate was identified from the largest image intensity gradient vector (oriented outwards of bone structures) along the selected ray. The exact center and inclination of the sacral endplate were then found in an optimization procedure. An elliptical plane that was centered in the currently identified point on the surface of the sacral endplate was determined by optimizing the sagittal and coronal inclination of the plane according to the largest sum of image intensities within the plane, which resulted in the inclination of the sacral endplate. Then, within the resulting plane, a new center point was defined as the current center of the sacral endplate by searching for image intensities and corresponding image intensity gradient vectors representing the edges of the sacrum in the left and right, and in the anterior and posterior direction of the center point. The procedure for defining the best fit plane and the best located center point of the sacral endplate was repeated until a relatively small difference in results was detected between two consecutive iterations (Fig. 3).
Fig. 3. The determination of the exact center and inclination of the sacral endplate in 3D, shown in its mid-sagittal (top), mid-coronal (middle) and mid-axial (bottom) CT cross-section as (a) original images, (b) magnitudes of image intensity gradient vectors, and (c) original images with the obtained center and inclination of the sacral endplate.

**Computerized determination of the left and right ischial axis in 3D**

From the identified center of each (left or right) femoral head, the superior endpoint of the corresponding ischial axis was initialized along a line at 30° above the hip axis (i.e. the line connecting the centers of both femoral heads) and 15 mm from the edge of the femoral head (represented by the sphere determining its size) into the pelvis. This point was then used to initialize a truncated elliptical cone (i.e. a conical cylinder) of length 100 mm and with equal initial superior and inferior radii of 10 mm. The inclination and size of this cone were then optimized according to image intensities and image intensity gradient vectors captured within the cone. It is important to note that the aim was not to segment each ischium, but to find its inclination represented by its axis. As a result, the axial location of the superior part of the cone, as well as the length of the cone, were fixed, while its inclination in 3D, and its superior and inferior radii were optimized to best fit each ischium in the CT image. Moreover, the optimization was performed simultaneously for the left and right ischium, as the sagittal inclination of both cones measured from the hip axis was represented by one angle to obtain a single inclination value, used for the computation of the ischio-iliac angle (Fig. 4).
Fig. 4. Consecutive axial CT cross-sections ($\Delta z$ denotes the offset from the first cross-section) with the obtained left and right femoral heads (cross-sections of spheres, in yellow), and of the obtained left and right ischia (cross-sections of truncated elliptical cones, in red).
**Computation of the ischio-iliac angle**

Before computing the ischio-iliac angle, multiplanar 3D image reformation was performed to obtain the superposition of the femoral heads in the sagittal view. As a result, the hip axis was observed as a non-inclined line and all anatomical structures were completely in line with the hip axis. Finally, the ischio-iliac angle was automatically calculated in the reformatted sagittal plane as the angle between the line connecting the hip axis (i.e. centers of femoral heads) with the center of the sacral endplate, and the line along the axes of both ischia (Fig. 5).

![Diagram of the ischio-iliac angle](image)

**Fig. 5.** The ischio-iliac angle (IIA) is defined in the reformatted sagittal plane, which is perfectly aligned with the hip axis, as the angle between the line connecting the hip axis and the center of the sacral endplate (blue lines), and the line along the axes of both ischia (red lines), shown in (a)-sagittal and (b)-coronal maximum intensity projection (MIP) images.