Automated Measurement of Pelvic Incidence from X-Ray Images

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Abstract. One of the most important parameters of sagittal pelvic alignment is the pelvic incidence (PI), which is commonly measured from sagittal X-ray images of the pelvis as the angle between the line connecting the midpoint of the femoral head centers with the center of the sacral endplate, and the line orthogonal to the sacral endplate. In this paper, we present the results of a fully automated measurement of PI from X-ray images that is based on the deep learning technologies. In each sagittal X-ray image of the pelvis, regions of interest (sacral endplate and both femoral heads) are first automatically defined, and then landmarks are detected within these regions, i.e. the anterior edge, the center and the posterior edge of the sacral endplate that define the line of the sacral endplate inclination, and the centers of both femoral heads with the corresponding midpoint representing the hip axis. From the hip axis, and the line along the sacral endplate and its center, PI is computed. Measurements were performed on X-ray pelvic images from 38 subjects (15 males/23 females; mean age 71.1 years), and statistical analysis of reference manual and fully automated measurements revealed a relatively good agreement, with the mean absolute difference ± standard deviation of $5.1 \pm 4.4^\circ$ and Pearson correlation coefficient of $R = 0.82$ (p-value below 10^{-6}), with the paired t-test revealing no statistically significant differences (p-value above 0.05). The differences between reference manual and fully automated measurements were within the repeatability and reliability of manual measurements, indicating that PI can be accurately determined by the proposed fully automated approach.

Keywords: Pelvic incidence · X-ray imaging · Deep learning

1 Introduction

Pelvic incidence (PI) is one of the most important parameters of sagittal pelvic alignment, and is represented by the angle between the line connecting the hip axis (i.e. the midpoint of the centers of both femoral heads) with the center of the sacral endplate, and the line orthogonal to the sacral endplate [1,2]. As such, it describes the relative position of the sacral endplate against the femoral heads, and therefore the anatomical characteristics of the pelvis in the sagittal plane

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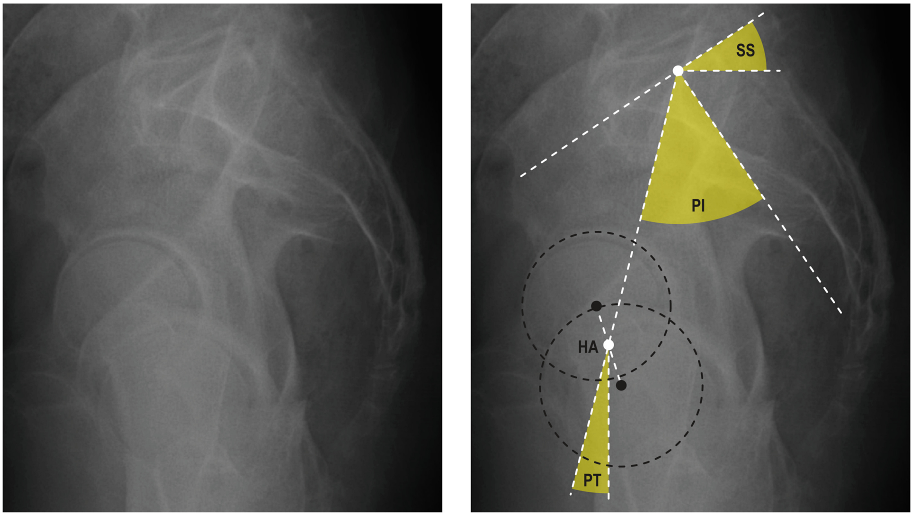
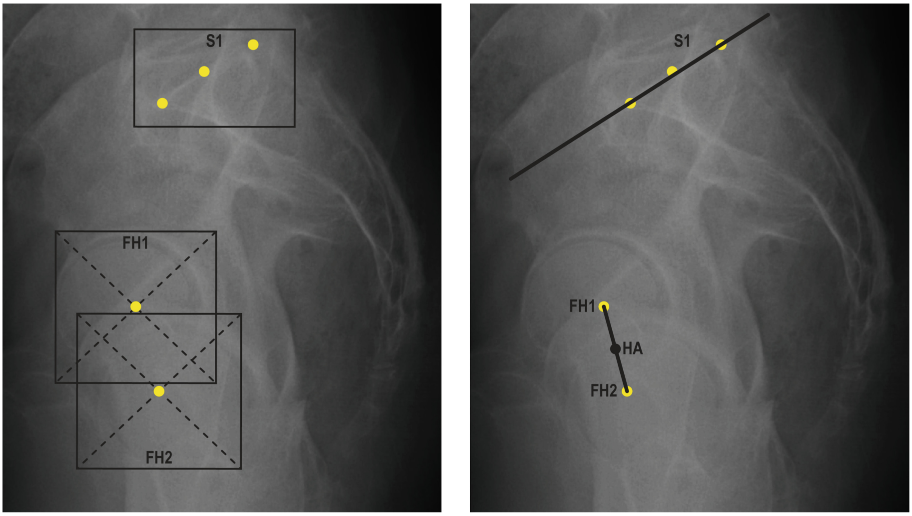
and the balance of the lumbar spine that rests on the sacrum. The mean PI for a healthy population is $47° - 57°$ with a standard deviation (SD) of around 10° [2], nevertheless, a very low PI ($35° - 44°$) means that the femoral heads are positioned just below the sacral endplate with the pelvis being narrow horizontally and large vertically (i.e. a vertical pelvis), while a very high PI (75°–85°) means that the femoral heads are position ahead of the midpoint of the sacral endplate with the pelvis being narrow vertically and large horizontally (i.e. a horizontal pelvis) [3]. Measurement of PI is most commonly performed in sagittal X-ray images of the pelvis (Fig. 1), however, it represents a relatively tedious and subjective task, mostly because of the quality of the acquired images and their projective nature [4–6]. Although several software packages exist for computerized measurement of PI [4, 7–10], the resulting measurements are still based on manually defined points, geometrical constructs and statistical modeling, and therefore are not fully automated. In this paper, we present the results of a fully automated measurement of PI from X-ray images of the pelvis.



(a) (b)

Fig. 1. (a) A sagittal X-ray of the pelvis. (b) The parameters of the pelvic incidence (PI) as the angle between the line connecting the hip axis (HA, the midpoint between the centers of both femoral heads) with the first sacral (S1) endplate center and the line orthogonal to the S1 endplate, sacral slope (SS) as the angle between the line along the S1 endplate and the horizontal reference, and pelvic tilt (PT) as the angle between the line connecting the HA with the S1 endplate center and the vertical reference. The following relationship is established: $SS + PT = PI$.



(a) (b)

Fig. 2. Fully automated measurement of pelvic incidence. (a) The region of interest (ROI) for the first sacral (S1) endplate and for both femoral heads (FH1, FH2), with landmarks within each ROI: the anterior edge, the center and the posterior edge on the S1 endplate, and the centers of both femoral heads. (b) The sacral slope is determined by fitting a line to the landmarks. The hip axis (HA) is determined as the midpoint between the centers of the femoral heads.

2 Methodology

The automated measurement of PI from X-ray pelvic images is based on deep learning and consists of three stages,[1] i.e. the identification of the regions of interest (ROIs), determination of distinctive points or landmarks, and measurement of PI (Fig. 2). The first stage (Fig. 2(a)) is the automated identification of ROIs that contain the observed anatomical structures, i.e. the first sacral (S1) endplate and each individual femoral head, in the given X-ray image. For this purpose, we designed a special architecture of convolutional neural networks (CNNs) [11] that was trained on a set of X-ray images with predefined ROIs. The second stage (Fig. 2(a)) is the automated determination of landmarks, i.e. the center of each femoral head and the anterior edge, the center and the posterior edge of the S1 endplate, within the corresponding ROIs obtained in the first stage. For this purpose, we designed a second CNN architecture [12] that was trained on a set of X-ray images with predefined landmarks. The third stage (Fig. 2(b)) is the automated determination of the line along the S1 endplate, which is obtained by least square fitting to the landmarks defined on the S1 endplate in the second

[1] Due to a copyright agreement, we cannot entirely disclose the technical details of our methodology. We therefore invite the reader to focus on the clinical application and the obtained results.

stage, and the determination of the hip axis as the midpoint between the centers of both femoral heads. From the acquired data, we can measure PI as the sum of SS and PT.

3 Results

The automated measurement of PI was evaluated on sagittal X-ray images of the pelvis from 44 subjects (16 males/28 females; mean age 71.5 years, age range 49–85 years) that were acquired at Charité University Hospital (Berlin, Germany) by the Kodak Elite CR and Kodak DRX-Evolution scanners (Carestream Health; Rochester, New York, USA) for purposes not related to this retrospective study. For each image, reference manual measurements of PI, SS and PT were obtained, which allowed for a statistical comparison with the fully automated measurements. However, reference manual measurements could not be reliably performed in six out of 44 X-ray images because of the partially visible femoral heads in two cases, and ambiguities in the determination of the center and inclination of the S1 endplate in four cases. As a result, these images were excluded from statistical comparison, which was in the end performed for images of 38 subjects (15 males/23 females; mean age 71.1 years, age range 49–85 years). The results are presented in terms of the mean absolute difference (MAD), the corresponding SD and the Pearson correlation coefficient (R). Statistical significance was observed through the paired t-test, with the level of significance set to $p < 0.05$.

Reference manual measurements amounted to $54.4 \pm 11.8°$ (mean ± SD) for PI, $35.0 \pm 8.7°$ for SS and $19.4 \pm 8.5°$ for PT, which is in accordance with existing population studies [2]. With the described fully automated approach we then successfully measured the same parameters, which amounted to $54.0 \pm 10.4°$ for PI, $34.3 \pm 8.6°$ for SS and $19.6 \pm 8.5°$ for PT. Statistical analysis of the agreement between manual and automated measurements is presented in Table 1 and Fig. 3.

Table 1. Statistical comparison between reference manual and fully automated measurements of pelvic incidence (PI), sacral slope (SS) and pelvic tilt (PT) from X-ray images of the pelvis of 38 subjects in terms of the mean absolute difference (MAD), standard deviation (SD), Pearson correlation coefficient (R), and p-value of the paired t-test.

	Pelvic incidence (PI)	Sacral slope (SS)	Pelvic tilt (PT)
MAD ± SD (°)	5.1 ± 4.4	5.2 ± 3.8	2.2 ± 2.0
R (p-value)	0.82 ($<10^{-6}$)	0.73 ($<10^{-6}$)	0.94 ($<10^{-6}$)
Paired t-test (p-value)	0.691	0.519	0.627

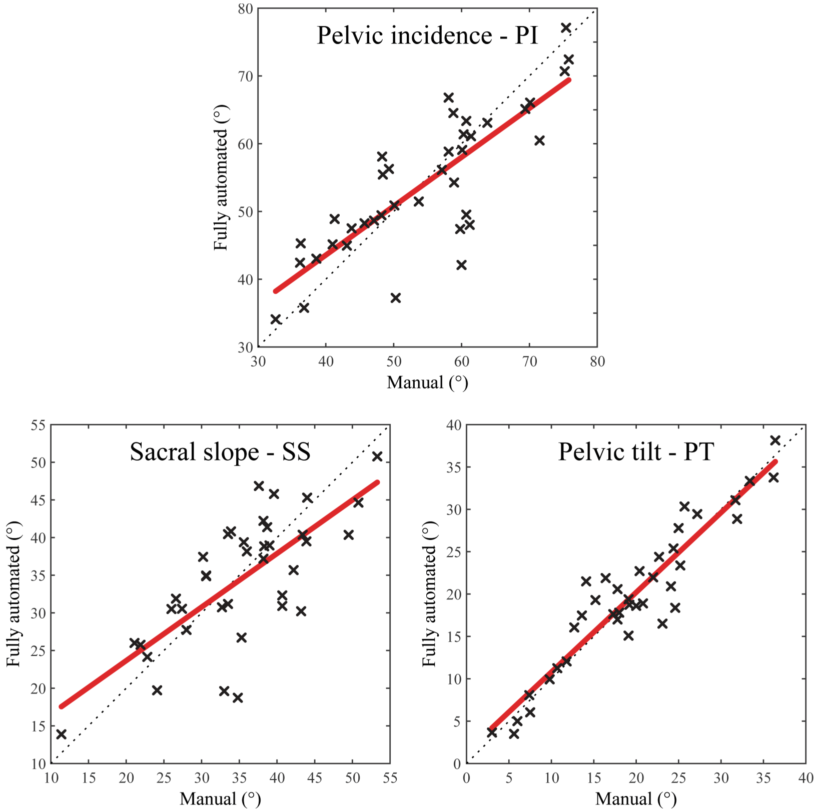


Fig. 3. Agreement between the manual and fully automated measurements.

4 Discussion

The determination of PI from X-ray images is a relatively demanding process because the projective nature of X-ray imaging causes a virtual superposition of the anatomical structures of interest. Moreover, different characteristics that originate from the natural biological variability of the human anatomy may also introduce ambiguities in the measurement process. Software packages that allow for computerized measurement of PI by manually drawing geometrical constructs (e.g. points, lines, circles) [4,7–10] proved to be more reproducible and reliable than measurements from plain X-ray films, as Vialle et al. [7] reported a mean reproducibility of $R = 0.86$ ($p = 0.014$) and $R = 0.96$ ($p < 0.001$), and a mean reliability of $R = 0.65$ ($p = 0.024$) and $R = 0.99$ ($p<0.001$) respectively for manual measurements of PI from plain X-ray films and digital X-ray images. Dimar II et al. [8] reported an even worse agreement, as they obtained a mean reproducibility of $R = 0.65$, 0.71 and 0.55 and a mean reliability of $R = 0.29$, 0.61 and 0.44 respectively for PI, SS and PT, while the agreement with computerized measurements was estimated to $R = 0.59$, 0.72 and 0.63, respectively.

Although computerized approaches improved the reproducibility and reliability, the measurement itself remains a relatively time-consuming and subjective task that highly depends on the experience of the observer. On the other hand, a fully automated measurement approach has not been yet presented, mostly because it represents a challenging problem from the perspective of automated analysis of X-ray images.

The described approach solves, to a certain degree, the afore mentioned problem. Statistical analysis (Table 1) revealed that there are no statistically significant differences between reference manual and fully automated measurements of PI, as well as of SS and PT. We can also conclude that the fully automated measurements are in agreement with reference manual measurements in the reliability range of classical and computerized manual measurements [7,8], as the correlation was good ($0.7 < R < 0.9$) in the case of PI and SS, and very good ($0.9 < R < 1.0$) in the case of PT. Nevertheless, high correlation and a relatively low MAD do not necessarily mean that the fully automated measurements are correct, moreover, a difference of around $5°$ may originate from the reproducibility and reliability of manual measurements [2]. The high agreement of reference manual and fully automated measurements results from applying the state-of-the-art deep learning technologies. It is also important to note that the proposed approach does not make use of already implemented techniques, but is refined with a detailed knowledge of CNN architectures, corresponding criterion functions and methods of supervised learning, as well as a detailed knowledge of spine and pelvis anatomy, and measurement of geometrical parameters from medical images.

5 Conclusion

In this paper, we presented the results of a fully automated measurement of PI from sagittal X-ray images of the pelvis. The results indicate that by this approach, it is possible to accurately determine PI, as the differences against reference manual measurements were within the range of the reproducibility and reliability of manual measurements. Nevertheless, the proposed fully automated approach cannot completely replace the visual review and confirmation of the measured values by an observer, as the differences may be in certain cases quite large, mostly due to the natural biological variability of the human anatomy and the characteristics induced by X-ray imaging.

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