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Method Article

# An anthropometric-based method for the assessment of pelvis position in three-dimensional space

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ABSTRACT

Determining the pelvis position remains a challenge for clinical therapists and researchers mainly due to the difficulty in assessing its potential triaxial rotations in the upright standing posture. The method described in this study aims to determine the position of the pelvis in the upright standing posture by calculating the Euler/Cardan angles of pelvic rotations based on the triaxial coordinates of the anterior superior iliac spines and the pubic symphysis. The coordinates of these bony landmarks were determined with two laser distance meters and a standard metric ruler, all mounted on a custom-made structure. The calculations of all Euler/Cardan angle rotation sequences for both the internal and external rotations of the pelvis were performed by developing an algorithm that executed via a computer program specifically designed for the purpose of this study. The validity of the algorithm was tested by comparing the actual angles of known positions at which an anatomical model of the pelvis was placed with the calculated angles. Our findings revealed $<1°$ differences between the actual and the calculated angles of pelvis rotations regardless of the axis around which it was rotated suggesting that the proposed method can be used for clinical and research purposes.

- The triaxial coordinates of pelvis bony landmarks can be measured anthropometrically using simple measuring instruments
- Pelvis posture can be determined in 3D space with great accuracy by means of the Euler/Cardan angles



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| Resource availability: | *Non applicable* |

## Method details

The pelvis position by means of the intrinsic and extrinsic rotations performed about the *x*-, *y*-, and *z*-axis was determined by calculating the Euler/Cardan angles based on the coordinates of pelvis bony landmarks, namely the right and left anterior superior iliac spines (ASIS-R and ASIS-L) and the pubic symphysis (PS). The intrinsic angles correspond to elemental rotations that always occur on the rotating coordinate system which is solidary with the moving object. The extrinsic angles correspond to elemental rotations that occur relative to the original coordinate system which remains motionless.

The coordinates of the pelvis bony landmarks were determined on a three-dimensional Cartesian coordinate system, the origin (0) of which located to an aluminium rectangular base fixed on a cylindrical tube with a built-in gear rack (i.e. a rectangular shaped rod fitted on one side with teeth just like a gear). Small adjustments to the position of the base on the vertical axis (z-axis) could be achieved via a gear that was engaged in the teeth of the rack by rotating a solid disc hand-wheel with a revolving handle. The rectangular base and the cylindrical tube on which it was fixed were mounted on a custom-made apparatus, designed to slide manually on a 2-m high stainless steel rectangular tube in the vertical direction. This arrangement enabled the rectangular base to be placed and adjust in greater heights. The rectangular tube was also mounted vertically via a wooden base on four telescopic ball bearing runners, which were housed in a 120 cm (L) × 67 cm (H) × 25 cm (W) rectangular wooden box. This arrangement allowed the rectangular tube, and therefore the apparatus on which the aluminium base was fixed, to slide alongside the box (x-axis). The rectangular wooden box was fixed to one side of a 120 cm × 120 cm wooden platform. A rotating base fixed on the opposite side of the platform was used to place anatomical models that used to test the validity of the method and for clinical measurements in humans (Fig. 1).

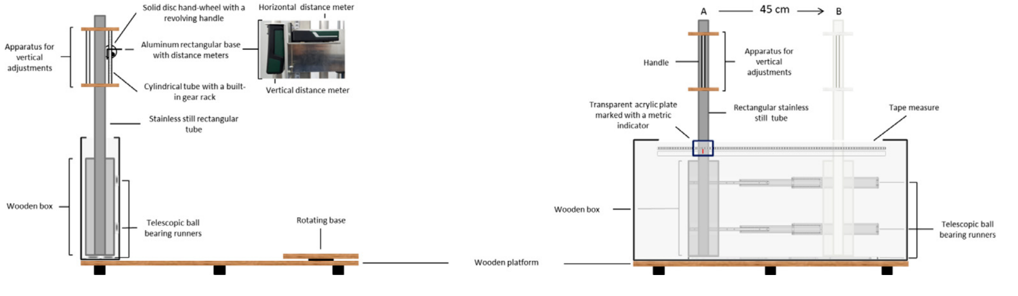


**Fig. 1.** Drawings of the custom made structure specifically designed to enable anthropometric measurements of the coordinates of spesific bony landmarks of the pelvis.

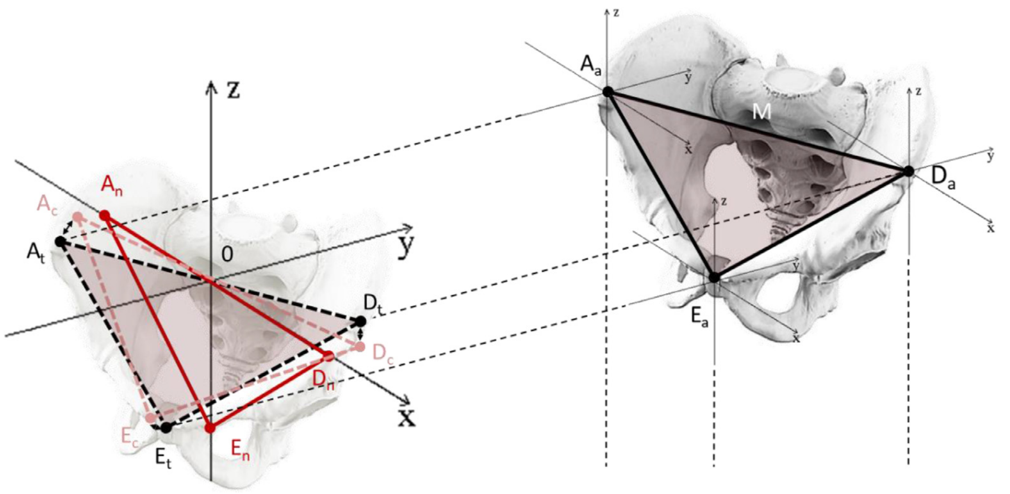


**Fig. 2.** Schematic presentation of the method used to determine the orientation of pelvis. $A_aD_aE_a$: Actual measured triangle (black solid line with shaded area); $A_tD_tE_t$: Transferred triangle (black dashed line with shaded area) i.e. the $A_aD_aE_a$ triangle after been transferred to the origin of axes; $A_nD_nE_n$: Neutral triangle (red solid line) i.e. the $A_aD_aE_a$ triangle set on the triaxial coordinate system; $A_cD_cE_c$: Calculated triangle (light red dashed line) with the closest coordinates to the coordinates of the $A_tD_tE_t$ triangle.

## Determination of the coordinates of the pelvis bony landmarks

The determination of the ASIS-R and ASIS-L as well as the PS coordinates on the *x*-, *y*- and *z*-axes was performed using (i) a metric ruler that was placed alongside the upper surface of the rectangular wooden box and (ii) two commercially available digital laser distance meters (PLR 25 Digital Laser Measure, Bosch, Leinfelden-Echterdingen, Germany), with measurement range 0.05 – 25.00 m and measurement accuracy ±2.0 mm), fitted on the horizontal and vertical surfaces of the aluminium rectangular base. Once a bony landmark of the pelvis was detected with the laser beam of the horizontally placed distance meter, by sliding the rectangular tube alongside the wooden box and adjusting the height of the base, the researcher (i) marked the position of the rectangular tube on the ruler using a built-in metric indicator (*x*-axis coordinate) and (ii) measured the horizontal and the vertical distances from the respective distance meters to the detected bony landmark (*y*-axis coordinate) and the upper surface of the wooden box (*z*-axis coordinate), respectively. All measurements were recorded to the closest millimetre.

## Determination of the rotation angles of the pelvis

The angles $\psi$, $\theta$ and $\varphi$ of pelvis rotations about the *x*-, *y*-, and *z*-axes, respectively were determined by means of a set of Euler/Cardan angles that produced a triangle $A_cD_cE_c$ with coordinates that closely approximated the coordinates of the triangle $A_aD_aE_a$ that actually measured (triangle whose vertices correspond to the bony landmarks of the pelvis) using the following expression (Fig. 2, Eq. 1)

$$\begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} = \mathrm{R_z}(\varphi) \cdot \mathrm{R_y}(\theta) \cdot \mathrm{R_x}(\psi) \begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix} \tag{1}$$

for the sequence of extrinsic rotations about the *x*-*y*-*z* axes where

$$\begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix}$$

the calculated coordinates of a vertex of the $A_cD_cE_c$ triangle that closely approximated the coordinates of the same vertex of the $A_tD_tE_t$ triangle i.e. the $A_aD_aE_a$ triangle after being transferred to the origin of axes

$$R_z(\varphi) = \begin{bmatrix} \cos(\varphi) & \sin(\varphi) & 0 \\ -\sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}, R_x(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin(\psi) \\ 0 & -\sin(\psi) & \cos(\psi) \end{bmatrix}$$

the Euler/Cardan matrices for the sequence of extrinsic rotations about the *x-y-z* axes and

$$\begin{bmatrix} N_x \\ N_y \\ N_z \end{bmatrix}$$

the coordinates of a vertex of the $A_nD_nE_n$ (neutral) triangle i.e. the coordinates of a vertex of the $A_aD_aE_a$ triangle that was set on the triaxial coordinate system

The coordinates of each vertex of the triangle $A_cD_cE_c$ were calculated for every sequence of extrinsic rotations (*x-y-z, x-z-y, y-z-x, y-x-z, z-x-y, z-y-x*) and the corresponding intrinsic rotations (*x-y′-z″, x-z′-y″, y-z′-x″, y-x′-z″, z-x'-y″ z-y′-x″*) by developing a computer program written in Python 3.5 using similar expressions.

The $A_tD_tE_t$ triangle was set on the triaxial coordinate system by locating the inter-ASISs midpoint M (centre) of the $A_aD_aE_a$ triangle at the origin of axes after calculating its offset, that is the distances between M and the origin of axes on the *x*-, *y*-, and *z*-axes based on the expression (Eq. 2)

$$center = \left[ \frac{(Ax + Dx)}{2}, \ \frac{(Ay + Dy)}{2}, \ \frac{(Az + Dz)}{2} \right] = [center_x, \ center_y, \ center_z] \tag{2}$$

The coordinates of the vertices of the $A_nD_nE_n$ triangle $A_n$(-AD/2, 0, 0) and $D_n$(AD/2, 0, 0) on the x-axis and $E_n$(AD/2-MD, 0, -EM) on the z-axis were calculated based on the coordinates of the $A_aD_aE_a$ triangle using the following expressions Eq. 3-(6)

$$AD = \sqrt{\left[ (Ax - Dx)^2 + (Ay - Dy)^2 + (Az - Dz)^2 \right)]} \tag{3}$$

$$AE = \sqrt{\left[ (Ax - \mathrm{E}x)^2 + (Ay - \mathrm{E}y)^2 + (Az - \mathrm{E}z)^2 \right)]} \tag{4}$$

$$DE = \sqrt{\left[ (Dx - \mathrm{E}x)^2 + (Dy - \mathrm{E}y)^2 + (Dz - \mathrm{E}z)^2 \right)]} \tag{5}$$

$$EM = DE \times sin(\varphi) \tag{6}$$

where,

*AD, AE* and *DE* the lengths of the sides, *EM* the length of the perpendicular to the side *AD* of the triangle $A_aD_aE_a$ and $\varphi = acos(\frac{DE^2 + AD^2 - AE^2}{2 \times DE \times AD})$

In order to reduce the calculation time, a graph algorithm was implemented based on which a very large part of the solution graph was rejected resulting in the rapid production and recording of the probable solutions for each one of the sequences of intrinsic and extrinsic rotations in a file. Based on this approach the orientation of the pelvis was determined by calculating the coordinates that closely approximate the coordinates of the $A_tD_tE_t$ triangle using a range of angles with a low resolution (every 10°). Thereinafter a range of angles with progressively higher resolutions was used (5.0°, 2.5°, 1.0°, 0.1° and 0.01°) but only within the range of angles where a more probable solution was previously detected. The most probable solution was the one that, for a given set of rotation angles, yielded the smallest error i.e. the smallest sum of the differences between the coordinates of the vertices of the calculated $A_c$,$D_c$,$E_c$ and the transferred $A_t$,$D_t$,$E_t$ triangle (Eq. 7)

$$\mathrm{Error} = (\mathrm{dD_x} + \mathrm{dA_x} + \mathrm{dE_x}) + \left(\mathrm{dD_y} + \mathrm{dA_y} + \mathrm{dE_y}\right) + (\mathrm{dD_z} + \mathrm{dA_z} + \mathrm{dE_z}) \tag{7}$$

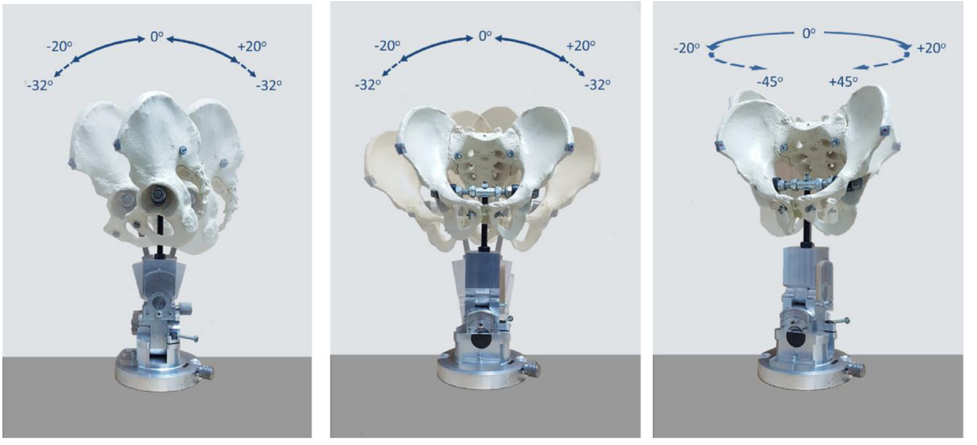


**Fig. 3.** Aluminium base used to place the anatomical model in predetermined positions in the (a) sagittal, (b) frontal, and (c) horizontal plane.

## Method validation

The method that enabled the determination of pelvis position based on anthropometric measurements of the bony landmarks of the pelvis was validated by comparing the angles of known positions of the pelvis (actual) with the angles derived with the algorithm (calculated). In this context, an anatomical model of the pelvis was placed in predetermined positions using an aluminium base specifically designed for the purpose of this study. The base consisted of three parts connected in such a way that they could be rotated manually either isolated or in combination with each other. The lower (bottom) part could be rotated 45° around the *z*-axis, while the middle and the upper part on which the anatomical model of the pelvis was attached and fixed with screws could be rotated 32° around the *y*- and *x*-axes. Transparent acrylic plates marked with angle-indicators placed on each part of the device enable the identification of the angle in which the anatomical model was placed with an accuracy of 0.5° (Fig. 3).

The device was placed on the platform against the apparatus before the commencement of the measurements and secured in the neutral position (i.e. a position of the pelvis where the ASISs and PS are at a level perpendicular to the ground) only when the distances of the ASISs and the PS from the horizontally placed distance meter were equal to each other. The Euler/Cardan angles were calculated under seven different conditions by rotating the anatomical model of the pelvis around one axis (conditions A, B and C for individual rotations of the pelvis around the *x*-, *y*- or *z*-axis, respectively), two axes (conditions D, E and F for combined rotations of the pelvis around the *x*- and *y*-axes, the *y*- and *z*- axes, or the *x*- and *z*-axes, respectively), and three axes (condition G for combined rotations of the pelvis around the *x*-, *y- and z*-axes), at a range of 40° (20° on either side of the pelvis neutral position). For pelvis rotations around one axis, the anatomical model was placed in 20 different positions with a difference of 2° from one position to the other. The anatomical model of the pelvis was also placed in 20 randomly selected positions with combined rotations either around two or three axes. The twenty different positions of the pelvis in each of the seven conditions (A-G) evaluated for the validity of the method led to 140 different calculations of the Euler/Cardan angles for the intrinsic and 140 for the extrinsic rotations of the pelvis that were ultimately included in the analysis (Fig. 3).

## Data analysis and results

Comparisons between the six sequences of the intrinsic and extrinsic rotations, regarding the differences between the actual and the calculated Euler/Cardan angles of pelvic rotations in all conditions tested, were assessed with one-way repeated measures ANOVA. The agreement between the actual and the calculated angles based on the optimal sequence of rotations (i.e. the sequence of rotations around the *x*-, *y*- and *z*-axes that reveal a set of angles that best match the angles of an actual pelvic position) was examined using the Intraclass Correlation Coefficient (ICC 3,1) [1] and the Bland and Altman's 95% Limits of Agreement (95%LoA) method [2]. The ICC model (3,1) was used in the context that the two methods used to determine pelvic position (actual and calculated) were the only ones under investigation with only one measurement being performed with each of them. Intraclass correlation coefficients values of <0.5 were indicative of poor reliability, values between 0.5 and 0.75 indicated moderate reliability, values between 0.75 and 0.9 indicated good reliability, and values >0.90 indicated excellent reliability [3]. The 95% LoA calculated using the expression, $\bar{d} \pm 2SD$ where $\bar{d}$ and $SD$ the mean (systematic bias) and the standard deviations of the mean difference between the actual and the calculated angles of pelvic rotation in each one of the axes. The differences between the actual and calculated angle were assessed using paired t-tests [2]. The chi-squared test was used to investigate whether there is an association between the pelvic rotations (intrinsic and extrinsic) and the optimal sequence.

The differences between the six sequences regarding the agreement between the actual and the calculated angles (systematic bias) were significant for pelvic rotations around the *x*- and *y*-axes ($p<0.001$) in condition C. The differences between the six sequences regarding the systematic bias were also significant for pelvic rotations around all axes ($p<0.001$) in conditions D, E and F (Table 1).

The agreement between the actual and the calculated angles of rotation was greater when the optimal sequence was taken into account. In this case, the ICC (3,1) between the actual and the calculated angles was excellent (1.0) in all conditions tested (A-G) with the systematic bias and the 95% LoA being, in general, less than ±1.0°. The greatest systematic bias (-0.23°) was obtained for pelvic rotation around the *x*-axis in the C condition and the wider 95%LoA (-0.65° – 0.60°) were obtained for pelvic rotation around the *y*-axis in the E condition. From a mathematical point of view, the Euler/Cardan angles for the internal and the external rotations of the pelvis were identical. However, there was a significant association between the type of pelvis rotation (intrinsic and extrinsic) and the optimal sequence, with the *x*-*y*-*z* and the *z*-*y*-*x* being the sequences that provided more frequently the closest agreement between the actual and the calculated angles for the external (61/140) and internal rotations of the pelvis (46/140), respectively (Table 2). In general, these sequences provided more than half of the times the closest agreement between the actual and the calculated angles (167/280) for both internal and external rotations.

## Additional information

The position of the pelvis in the relaxed upright posture has been assessed by many clinical therapists and researchers who aimed to investigate (i) its anatomical and kinesiological relationship with the head-trunk-upper extremities complex and/or the lower extremities [4–7], (ii) its response or adaptation to skeletal asymmetries (e.g. leg length discrepancy, scoliosis) and the tensions exerted by the musculoligamentous structures under weight-bearing conditions [8,9] and (iii) its contribution to painful musculoskeletal syndromes [10–12] or other clinical conditions [13]. In general, the position of the pelvis has been assessed with direct or indirect non-invasive, safe, and inexpensive methods requiring simple equipment (e.g. standard tape measure, callipers). Directly, pelvis position has been determined in terms of pelvic tilt and obliquity by measuring the inclination of the ASIS-to-PSIS line and the inter-ASIS line, respectively relative to the horizontal plane using various inclinometers [5,6,14,15]. Other authors measured pelvic tilt and obliquity as well as the ROM of the pelvis indirectly by calculating trigonometrically the angle formed between the aforementioned lines (i.e. ASIS-to-PSIS line and the inter-ASIS line) and the horizontal plane [4,7,10,16] Sanders and Stavrakas, (1981) [7], in an early study, introduced a method to determine pelvic tilt in the upright standing posture by calculating the angle formed between the ASIS-to-PSIS line and the horizontal plane. In fact the authors in this study calculated the sine of the angle of the right triangle whose hypotenuse corresponded to the ASIS-to-PSIS distance and the opposite side to the difference in height between the ASIS- and the PSIS-to-the-floor distances. This method demonstrated adequate intrarater and interrater reliability [17,18] and it was used to determine the position and the ROM of the anterior

**Table 1**
Systematic biases ($\overline{d_x}$, $\overline{d_y}$, $\overline{d_z}$) and 95% Limits of Agreement ($\pm 2SD_x$, $\pm 2SD_y$, $\pm 2SD_z$) between the actual and the calculated Euler/Cardan angles for both the optimal and the individual sequences of intrinsic and extrinsic rotation(s) of the pelvis around one (A-C), two (D-F) and three axes (G), in a range of 20° on either side of the pelvis neutral position.

| $R_x$, $R_y$, $R_z$ | Actual pelvic rotations (°) | Calculated Euler/Cardan angles of pelvic rotations (°) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Optimal sequences SB (95%LoA) | *x-y-z* SB (95%LoA) | *x-z-y* SB (95%LoA) | *y-x-z* SB (95%LoA) | *y-z-x* SB (95%LoA) | *z-x-y* SB (95%LoA) | *z-y-x* SB (95%LoA) |
| **A** | -20 – 20, 0, 0 | $R_x$: | -0.01 (-0.39 – 0.38) | -0.01 (-0.40 – 0.37) | -0.01 (-0.40 – 0.37) | -0.01 (-0.40 – 0.37) | -0.01 (-0.40 – 0.37) | -0.01 (-0.40 – 0.37) | -0.01 (-0.40 – 0.37) |
| | | $R_y$: | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) |
| | | $R_z$: | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) |
| **B** | 0, -20 – 20, 0 | $R_x$: | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) |
| | | $R_y$: | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) | -0.02 (-0.48 – 0.43) |
| | | $R_z$: | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) |
| **C** | 0, 0, -20 – 20 | $R_x$: | -0.24 (-0.48 – 0.01) | -0.23 (-0.48 – 0.01) | -0.24 (-0.50 – 0.01) | -0.23 (-0.47 – 0.01) | -0.24 (-0.48 – 0.01) | -0.24 (-0.48 – 0.01) | -0.24 (-0.48 – 0.01)* |
| | | $R_y$: | -0.01 (-0.07 – 0.04) | -0.05 (-0.12 – 0.03) | -0.05 (-0.13 – 0.03) | -0.05 (-0.12 – 0.03) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00 - 0)* |
| | | $R_z$: | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) | 0.00 (-0.51 – 0.51) |
| **D** | -20 – 20, -20 – 20, 0 | $R_x$: | -0.06 (-0.41 – 0.54) | -0.10 (-0.63 – 0.44) | -0.21 (-0.43 – 0.86) | -0.06 (-0.46 – 0.58) | 0.06 (-0.46 – 0.58) | 0.17 (-0.27 – 0.61) | 0.06 (-0.46 – 0.58)* |
| | | $R_y$: | 0.00 (-0.41 – 0.41) | 0.17 (-0.28 – 0.63) | 0.19 (-0.30 – 0.69) | 0.00 (-0.39 – 0.40) | 0.00 (-0.38 – 0.39) | -0.19 (-0.72 – 0.33) | 0.00 (-0.38 – 0.39)* |
| | | $R_z$: | -0.04 (-0.22 – 0.14) | -1.47 (-3.73 – 0.80) | -1.40 (-3.55 – 0.76) | -0.04 (-0.23 – 0.14) | -0.10 (-0.78 – 0.57) | -1.35 (-3.61 – 0.91) | -0.04 (-0.22 – 0.14)* |
| **E** | 0, -20 – 20, -20 – 20 | $R_x$: | -0.09 (-0.29 – 0.12) | -2.12 (-6.89 – 2.64) | -0.43 (-1.13 – 0.27) | -1.99 (-6.69 – 2.71) | -2.38 (-7.18 – 2.42) | -0.34 (-0.87 – 0.19) | -0.28 (-0.68 – 0.12)* |
| | | $R_y$: | -0.03 (-0.65 – 0.60) | -0.21 (-0.89 – 1.31) | -0.11 (-0.95 – 0.74) | 0.18 (-0.86 – 1.23) | -0.44 (-1.59 – 0.72) | -0.12 (-0.91 – 0.66) | -0.12 (-0.91 – 0.66)* |
| | | $R_z$: | 0.03 (-0.55 – 0.61) | 0.29 (-1.26 – 0.68) | -0.01 (-0.60 – 0.59) | 0.32 (-0.59 – 1.22) | 0.34 (-0.63 – 1.31) | 0.01 (-0.56 – 0.58) | 0.03 (-0.58 – 0.63)* |
| **F** | -20 – 20, 0, -20 – 20 | $R_x$: | 0.05 (-0.55 – 0.65) | 0.19 (-0.54 – 0.92) | 0.20 (-1.51 – 1.12) | 0.21 (-0.51 – 0.92) | 0.00 (-0.92 – 0.93) | 0.00 (-0.92 – 0.93) | 0.06 (-0.58 – 0.69)* |
| | | $R_y$: | -0.06 (-0.34 – 0.22) | 1.78 (-5.19 – 1.63) | 1.69 (-5.30 – 1.92) | 1.81 (-5.47 – 1.84) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00)* |
| | | $R_z$: | 0.05 (-0.44 – 0.55) | -0.27 (-0.49 – 1.02) | 0.28 (-0.52 – 1.08) | -0.20 (-0.99 – 0.60) | 0.04 (-1.44 – 0.52) | 0.04 (-0.44 – 0.52) | 0.03 (-0.43 – 0.50)* |
| **G** | -20 – 20, -20 – 20, -20 – 20 | $R_x$: | -0.02 (-0.60 – 0.57) | 0.09 (-2.59 – 2.77) | 0.00 (-1.78 – 1.79) | 0.18 (-2.54 – 2.89) | -0.06 (-2.90 – 2.79) | 0.22 (-1.31 – 1.75) | 0.09 (-1.46 – 1.64) |
| | | $R_y$: | 0.08 (-0.43 – 0.59) | 0.32 (-4.10 – 4.74) | 0.20 (-4.34 – 4.74) | 0.20 (-4.31 – 4.70) | 0.01 (-0.73 – 0.76) | 0.03 (-0.72 – 0.77) | 0.16 (-0.56 – 0.88) |
| | | $R_z$: | -0.05 (-0.58 – 0.49) | -0.22 (-3.16 – 2.69) | -0.12 (-3.09 – 2.85) | -0.41 (-1.91 – 1.09) | -0.20 (-1.62 – 1.22) | -0.34 (-3.36 – 2.69) | -0.32 (-1.76 – 1.12) |

**Note:** $R_x$, $R_y$, $R_z$ = Pelvic rotations around the *x*-, *y*- and *z*-axis; SB: Systematic bias; 95%LoA = 95%Limits of Agreement; The negative sign (-) denotes posterior tilt, left side flexion and left rotation of pelvis.

* $p<0.001$

**Table 2**
Frequency of sequences revealing the greatest agreement between the actual and the calculated angles for intrinsic and extrinsic pelvic rotations (N=280).

| Pelvic rotations | Sequence | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | xyz | xzy | yxz | yzx | zxy | zyx | |
| Intrinsic | 34 | 7 | 15 | 27 | 11 | 46 | 140 |
| Extrinsic | 61 | 10 | 20 | 8 | 15 | 26 | 140 |
| **Total** | **95** | **17** | **35** | **35** | **26** | **72** | **280** |

and posterior tilt of the pelvis [18] as well as the relationship between the pelvic tilt and the strength or the tension developed by the neighbouring soft tissue structures [9]. Other authors determine the asymmetry of the pelvis with indices that calculated based on the inter-ASIS and inter-PSIS distance as well as the ASIS- and PSIS-to-the-floor heights [4,10,16]. These indices indicated frontal plane asymmetry, also known as lateral pelvic tilt or pelvic obliquity, in which one innominate bone is higher than the other, and sagittal plane asymmetry, also called iliac rotation, in which one innominate bone is rotated anteriorly or posteriorly with respect to the other [4,5,16].

However, many reasons make these methods incomplete and inaccurate, if not incorrect. This is attributed to the fact that the position of the pelvis was usually determined at one plane at a time, mainly in the sagittal or in the frontal plane but not in the horizontal plane. Failure to determine the position of pelvis in three dimensions, since the pelvis is likely to demonstrate a certain amount of rotation in more than one axis at the same time, may obscure the true effect of skeletal asymmetries, muscle imbalances and/or clinical syndromes on it, affecting the decisions that will determine their treatment. Previous anatomical studies [19] have also shown great inter-individual variability regarding the inclination of the ASIS-PSIS line relative to the horizontal plane (0° to 23°) with the pelvis in the neutral position, i.e. a position where the ASISs and the PS are in a plane that is vertical to the ground with an individual in the upright standing posture. These findings showed that although the increased slope of the ASIS-to-PSIS line relative to the horizontal plane (ASIS moves inferiorly and the PSIS superiorly) indicates that the pelvis is tilted anteriorly and the decreased slope of the ASIS-PSIS line that the pelvis is tilted posteriorly (ASIS moves superiorly and the PSIS inferiorly), the pelvis may in fact be in the neutral position. Furthermore, it would be equally inappropriate to determine the position of the pelvis in the upright standing posture based on the anatomical landmarks traditionally used in the 3D analysis of pelvic movements, such as the centre between PSISs or a point above the second sacral bone, since the inclination of the pelvis is not related to the inclination of the sacrum [20]. On the other hand, even though the actual position of the pelvis can be determined more accurately based on the relative position of the ASIS and PS, very few authors have used this approach in research studies by applying either an adjustable calliper in conjunction with an inclinometer [8] or a portable ultrasound device [21] specifying, however, only the pelvic tilt.

The proposed method revealed that the Euler/Cardan angles, calculated based on the anthropometrically designation of the coordinates of specific pelvis bony landmarks, can accurately determine the position of the pelvis and therefore it can be used for clinical and research purposes. Based on the systematic biases and the 95%LoA the calculated angles were similar to the actual angles of pelvic rotations among sequences in conditions A, B and G and in condition C but only for pelvis rotations around the $z$-axis, suggesting that there is no reason for choosing one sequence over any other. In contrast, the differences between the six sequences regarding pelvic rotations around the $x$- and $y$-axes in the C position and the rotations around all axes in the D, E and F conditions were significant. In any case, the 95%LoA indicated that the calculated angle of pelvis rotation could be from 7.2° greater to 4.7° lower than the actual angle, regardless of the axis around which the pelvis rotated. However, when the optimal sequence was taken into account the differences between the actual and the calculated angles of rotation were less than 1.0° with the $x$-$y$-$z$ and the $z$-$y$-$x$ being the sequences that revealed more frequently the greatest agreement between the two angles.

From a clinical standpoint, this method provides a great advantage over other methods as it enables clinicians and researchers to evaluate the pelvic position in the upright standing posture (i.e. weight-bearing position) where potential deviations/malalignments, imbalances, or pathologies of the joints and soft tissue structures of the lower extremity and the spine may affect it. This method can also be performed easily as it does not require specialized equipment but the use of a relatively simple structure, provided that it ensures accurate measurement of the distances between the pelvic landmarks and a fixed point in space. It can also be used to evaluate the position of other parts of the human body (e.g. scapula) whose rotation(s) around the three axes can affect or be affected by the position of the neighbourhood joints and the tension of the surrounding soft tissue structures. These advantages facilitate the use of this method in different populations for both the detection of possible skeletal abnormalities/deviations and the evaluation of the effectiveness of preventive and therapeutic programs by researchers without special skills apart from their ability to identify specific bony landmarks.

Nevertheless, the findings of the present study should be interpreted with caution due to some limitations related to the specific research conditions. These limitations are related to the definition of the coordinate axes and the selection of the intrinsic or extrinsic sequence of rotations that used to specify the position of the pelvis, as both parameters have been shown to lead to significantly different angular motion values. In contrast to other researchers and authorities [22–25], the axes of the coordinate system adopted in the present study were positive from left to right for the $x$-axis, from rear to front for the y-axis, and from below to the top for the $z$-axis. In addition, the position of the pelvis was not determined based on a specific sequence, which eventually may lead to an overestimation or underestimation of the actual position of the pelvis, as mentioned above, but on the optimal sequence. This eventually led to a high level of agreement between the calculated angles of pelvic rotation and the actual rotation of pelvis. The agreement between the actual and calculated angles may also be high because the pelvic bony landmarks were identified with great precision on an anatomical model. The location of these landmarks on the surface of the body may be affected by the skin and the subcutaneous body fat and may therefore be less accurate. This is very important as it can not only affect the identification and marking of a pelvic bony landmark, such as the pubic symphysis where a large amount of fat accumulates [26], but also estimate incorrectly the actual position of the pelvis. However, whether the palpation and marking of the pelvic bony landmarks can affect the calculation of angles remain to be investigated in a future study as, at this stage the researchers aimed to verify the accuracy of the algorithm developed to calculate the Euler/Cardan angles.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2022.101616.

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