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Standardization of hemipelvis alignment for *in vitro* biomechanical testing

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Running title: Hemipelvis alignment for biomechanical tests

1 **ABSTRACT**

2 Although *in vitro* biomechanical tests are regularly performed, the definition of a suitable
3 reference frame for hemipelvic specimens is still a challenge. The aims of the present
4 study were to: (1) define a reference frame for the human hemipelvis suitable for *in vitro*
5 applications, based on robust anatomical landmarks; (2) identify the alignment of a
6 hemipelvis based on the alignment of a whole pelvis (including right/left and male/female
7 differences); (3) identify the relative alignment of the proposed *in vitro* reference frame
8 with respect to a reference frame commonly used in gait analysis; (4) create an *in vitro*
9 alignment procedure easy, robust and inexpensive; (5) quantify the intra-operator
10 repeatability and inter-operator reproducibility of the procedure. A procedure to
11 univocally identify the anatomical landmarks was created, exploiting the *in vitro*
12 accessibility of the specimen's surface. Through the analysis on 53 CT scans (106
13 hemipelvises), the alignment of the hemipelvis based on the alignment of a whole pelvis
14 was analyzed: differences between male/female and right/left hemipelvises were not
15 statistically significant. To overcome the uncertainty in the identification of the acetabular
16 rim, a standard acetabular plane was defined. An alignment procedure was developed to
17 implement such anatomical reference frame. The intra-operator repeatability and the
18 inter-operator reproducibility were quantified with four operators, on male and female
19 hemipelvises. The intra-operator repeatability was better than 1.5°. The inter-operator
20 reproducibility was better than 2.0°. Alignment in the transverse plane was the most
21 repeatable. The presented procedure to align hemipelvic specimens is sufficiently robust,
22 standardized, and accessible.

23 **Keywords:** Anatomical reference frame; *in vitro* alignment; biomechanical testing;
24 hemipelvis; acetabular plane

25

26 1. INTRODUCTION

27 Reference frames and landmarks are of paramount importance in biomechanics ^{1;2}, to
28 allow comparisons between different clinical, numerical or *in vitro* studies.

29 Standardisation of the reference frame is extremely important for *in vitro* biomechanical
30 tests ²⁻⁶. It enables the correct alignment of the specimen and applied loads, in order to
31 reproduce a physiological loading condition. With the definition of reproducible testing
32 conditions, it is possible to compare different datasets of different studies.

33 Reference frames and landmarks for the pelvic bone are adopted in different applications
34 ^{1;2;7-14}. Reference frames used for the analysis of medical images are qualitative in most
35 cases ⁷⁻⁹. In example, to evaluate the pelvic tilt and sacral slope surgeons generally use
36 lateral radiographs, in combination with anatomical landmarks, assuming that the x-ray
37 frame is aligned with the anatomical planes. However, identification of these landmarks
38 depends on multiple factors like image quality and the position assumed by the patient.
39 For this reason, information that can be extracted from medical images is extremely
40 operator-dependent. *In vivo* applications (i.e. gait analysis) deal with reference frames
41 defined by palpable anatomical landmarks ^{1;10;11}. Landmarks routinely used in clinical
42 practice are the most accessible ones, while those that would cause patient discomfort are
43 avoided (e.g. pubic tubercle). Identification of the landmarks is heavily affected by the
44 presence of soft tissue. These considerations dictate some constraint to the reference
45 frames that can be adopted for *in vivo* applications. Surgical navigation adopts reference
46 frames both for the pre-operative planning and for intra-operative deployment ¹²⁻¹⁴.
47 Similarly, *in silico* applications rely on mathematical models derived from CT scans. Due
48 to the possibility to “navigate” the bone, identification of anatomical landmarks on CT

49 scans (which contain more detailed information) is more accurate. All the published
50 reference frames for the human pelvis^{4; 15; 16} rely on palpable landmarks that can be
51 reached non-invasively:

- 52 • Anterior Superior Iliac Spine (ASIS) defined as the most prominent point on the
53 iliac surface;
- 54 • Posterior Superior Iliac Spine (PSIS) defined as the upper and most posterior point
55 of the iliac crest;
- 56 • Pubic Tubercle (PT) defined as a prominent forward-projecting tubercle on the
57 upper border of the medial portion of the superior ramus of the pubis.

58 The Anterior Pelvic Plane (APP) is most widely used clinically¹⁷⁻¹⁹. It is defined by the
59 ASISs and the PTs. Despite the physiological range of tilt of the APP, it is assumed to be
60 roughly vertical in the standing position (anatomical neutral position, ANP)^{20; 21}.

61 A dedicated reference frame for *in vitro* biomechanical testing can rely on anatomical
62 landmarks that are accessed directly on the specimen (after the removal of soft tissues).
63 For this reason, *in vitro* reference frames are more robust and less operator-dependent than
64 *in vivo* ones, in which landmarks need to be identified non-invasively.

65 Despite the considerations above, only a few studies can be found where a suitable
66 reference frame is defined for the pelvis and hemipelvis^{22; 23}. It is very important to
67 underline that hemipelvic specimens are frequently adopted for *in vitro* purposes²⁴⁻²⁶. All
68 the reference frames described above rely on landmarks over the whole pelvis, and cannot
69 be implemented on a hemipelvis alone. Currently, there is no consensus on a specific
70 procedure for aligning a hemipelvis. Hence, in order to define a reference frame for the

71 hemipelvis, it is necessary to determine its alignment with respect to the whole pelvis.
72 The few previous studies dealing with hemipelvic specimens lack detail about its
73 alignment: Lewton *et al.* (2015) specified the direction of loads, defined as angles
74 measured relative to the long axis of the pelvis but no reference frame was defined ²³.
75 Preece *et al.* (2008) proposed a practical method based on the ANP; however more
76 information about the alignment procedure were not stated ²⁷.

77 The acetabular plane, which is defined as the plane tangent to the acetabular rim is often
78 used clinically ^{28; 29}. The alignment of the acetabular plane was investigated by Murray ³⁰.
79 In his work, he identified three definitions for acetabular inclination and anteversion:
80 radiological, operative and anatomical. Surgeons usually adopt the orientation of
81 acetabular plane as guide for surgical navigation, since it is easily identified through
82 clinical imaging ^{28; 29}. The acetabular plane was also adopted in different *in vitro* tests ²⁴⁻
83 ^{26; 31}. However, the irregular shape of the acetabular rim makes the identification of this
84 plane subjective ^{32; 33}.

85 Recently van Arkel *et al.* (2016) described an *in vitro* method to align a hemipelvic
86 specimen, based on the reference frame recommended by the International Society of
87 Biomechanics (ISB) ^{4; 22}. The proposed procedure requires first aligning the whole pelvis,
88 using four landmarks; the authors propose a procedure to dissect the specimen to obtain
89 two hemipelvises which preserve the same alignment previously identified for the whole
90 pelvis. The requirement of a whole pelvis as a starting point may be a limitation, as
91 sometimes only hemipelvic specimens are available.

92 The aims of the present study were to:

- 93 1. Define a reference frame for human hemipelvis that relies on robust anatomical
94 landmarks and is suitable for *in vitro* applications.
- 95 2. Identify the alignment of the hemipelvis based on the alignment of a whole pelvis.
96 This includes investigating differences in alignment between right and left, and
97 between male and female.
- 98 3. Identify the relative alignment of the newly proposed *in vitro* reference frame with
99 respect to the reference frame usually adopted in gait analysis ⁴.
- 100 4. Create an *in vitro* alignment procedure for hemipelvic specimens easy, robust and
101 inexpensive.
- 102 5. Quantify the intra-operator repeatability and inter-operator reproducibility of the
103 proposed procedure.

104 **2. MATERIAL AND METHODS**

105 An overview of the workflow is provided in Fig. 1. A practical *in vitro* identification of
106 suitable pelvic landmarks was created. Computed tomography (CT) scans of human
107 pelvises were analyzed to identify the alignment of selected landmarks of the hemipelvis
108 with respect to the whole pelvis. An *in vitro* alignment procedure was developed for
109 human hemipelvic specimens. The intra-operator repeatability and the inter-operator
110 reproducibility of the procedure were measured.

111 **2.1 *In vitro* identification of the landmarks**

112 As shown in different areas, identification of landmarks by palpation leaves a large
113 uncertainty and subjectivity³⁴. Direct *in vitro* identification of the landmarks can be more
114 accurate and precise. In order to implement a reproducible procedure, a robust method to
115 identify landmarks, suitable both for pelvis and hemipelvis, was adapted from those
116 commonly used *in vivo*⁴ (Fig. 2):

- 117 • The iliac and pubic regions must be brought in contact with a plane, while the iliac
118 wing is vertical. ASIS is found as the most external point of the iliac crest, which
119 is in contact against the plane.
- 120 • With the bone in the same position, PT is found as the point on the pubic tubercle
121 region, which is in contact against the plane.
- 122 • The iliac and ischial regions must be brought in contact with a plane while the iliac
123 wing is vertical. PSIS is found as the most external point of the iliac wing, which
124 is in contact against the plane.

125 **2.2 Identification of the anatomical alignment of the hemipelvis based on the** 126 **alignment of the whole pelvis, and comparison with ISB frame**

127 In order to adapt to a single hemipelvis the reference frame based on the APP (which is
128 defined for an whole pelvis), the alignment of the hemipelvis relative to the alignment of
129 its respective whole pelvis was identified. Furthermore, the relative orientation of the
130 proposed reference frame with respect to a reference frame commonly used in gait
131 analysis⁴ was measured based on the same landmarks. To the Authors' knowledge, this is

132 the first time that similar analysis was made to overcome limitations related to other
133 alignments such as those based on the acetabular plane.

134 **2.2.1 Analysis of patient CT scans**

135 Fifty-three CT scans were randomly selected among those taken for hip patients at Istituto
136 Ortopedico Rizzoli between 2014 and 2017. The patients were 25 male and 28 female,
137 27-88 years old. The scans had a voxel size of 0.7-0.8 mm. The scans were imported and
138 analyzed through nmsBuilder v1.0³⁵. For each scan, the landmarks (ASIS, PSIS and PT)
139 were identified on the whole pelvis according to the description above. The pelvises were
140 oriented in order to reach the ANP (tolerance 0.1 degrees). To measure the alignment of a
141 single hemipelvis relative to the alignment of its respective whole pelvis, two different
142 angles were measured (Fig. 3):

- 143 • β : the angle formed by the line connecting PT and ASIS with the transverse plane
144 of the whole pelvis;
- 145 • δ : the angle formed by the line connecting ASIS and PSIS with the sagittal plane
146 of the whole pelvis.

147 In addition, the relative orientation of the proposed reference frame with respect to the ISB
148 reference frame⁴ (which is commonly used in gait analysis) was measured in all scans
149 after identifying the mid-point of the two PSIS (mid PSISs): this consisted in a single
150 rotation (ξ), in a sagittal plane (Fig. 3).

151 To exclude outliers, Peirce's criterion was applied^{36;37}. Suspect data were checked
152 among subjects, for both angles. To test the procedure, three skilled operators processed

153 three CT scans three time each. To avoid any bias, the scan elaboration was performed on
154 different days between repetitions, so that the operator could not recognize previous
155 elaborations. To assess the intra-operator repeatability (i.e. when the same operator
156 repeatedly elaborates the same CT scan), the standard deviation between the three
157 repetitions was computed, for each of the operators and each CT scan. The repeatability
158 was computed as the root-mean-square-average between CT scans and operators. To
159 assess the inter-operator reproducibility (i.e. when different operators elaborate the same
160 CT scan), for each of the operators and each CT scan, the average value was computed out
161 of three repetitions. The reproducibility was computed as the standard deviation between
162 the operators.

163 The significance of differences between the right and left hemipelvises was tested with a
164 paired t-test for β and δ . Differences between male and female for β and δ were tested
165 with an unpaired t-test. A threshold of $p=0.05$ was assumed. Statistical analyses were
166 performed using MatLab (2009 Edition, MathWorks, Natick, MA, USA).

167 **2.3 Alignment procedure for the human hemipelvis**

168 In order to separately control the rotations, the hemipelvises were equipped with a
169 dedicated handle, which was clamped in a 6-degrees of freedom manipulator. The first
170 part of the procedure required aligning the landmarks with respect to horizontal and
171 vertical planes (Fig. 4):

- 172 • Vertical adjustment: the three landmarks were positioned at the same height (i.e.
173 using an adjustable plate and plasticine);

174 • Horizontal adjustment: ASIS and PT were positioned parallel to the edge of the
175 reference plane.

176 At this point the hemipelvis had a known alignment. To overcome the limitations of
177 defining the acetabular plane based on the acetabular rim ³⁰, a *standard acetabular plane*
178 was defined (SAP, see Appendix I). With the aim of aligning the hemipelvis with the
179 SAP horizontal, the specimen was subsequently rotated by two angles (Fig. 5) (see
180 Appendix I):

181 • Rotation in the posterior direction by $\Phi = 51^\circ$;

182 • Rotation in the medial direction by $\Omega = 10^\circ$.

183 **2.4 Assessment of the intra-operator repeatability and inter-operator** 184 **reproducibility**

185 To test the alignment procedure, hemipelvic bone specimens in solid foam (ERP
186 Mod.1291, ERP Mod.1294, Sawbones, Malmö, Sweden) were adopted. In order to
187 measure the alignment achieved, a squared plastic block was rigidly fixed on the
188 hemipelvises; the absolute orientation of its faces was measured, after the alignment,
189 through a goniometer (Art. 06.07503, IDF, Pontoglio (BS), Italy; precision: 0.1 degrees).

190 Four operators aligned the two specimens three times each. In order to evaluate the
191 robustness of the procedure two skilled operators (who performed at least one alignment
192 procedure) and two inexperienced operators were chosen. To avoid any bias, the
193 specimen orientation was modified between repetitions. To assess the intra-operator
194 repeatability, the standard deviation between the three repetitions was computed, for each

195 of the operators and each specimen. The repeatability was computed as the root-mean-
196 square-average between specimens and operators. To assess the inter-operator
197 reproducibility, for each of the operators and each specimen, the average value was
198 computed, out of three repetitions. The reproducibility was computed as the standard
199 deviation between the operators. Statistical analyses were performed using MatLab (2009
200 Edition, MathWorks, Natick, MA, USA).

201 **3. RESULTS**

202 **3.1 Alignment of hemipelvis based on the alignment of whole pelvis**

203 The landmarks could be easily identified in all the CT scans. Based on the Peirce's
204 criterion, five cases were excluded for β and none for δ . The intra-operator repeatability
205 was below 0.6° for β , and below 0.5° for δ . The inter-operator reproducibility was better
206 than $\pm 2.6^\circ$ for β and better than $\pm 3.8^\circ$ for δ .

207 The difference between right and left hemipelvises was on average 0.3° for β ($p > 0.7$) and
208 0.2° for δ ($p > 0.7$). In none of the 53 pelvises examined, a difference greater than 9° was
209 observed between the left and right hemipelvis for β and δ . The values of β in the female
210 subjects were 0.6° larger than for the males, but this difference was not statistically
211 significant ($p = 0.4$, Table 1). The values of δ were 0.1° larger for the female subjects than
212 for the males ($p = 0.9$, Table 1). The relative orientation of the proposed reference frame
213 with respect to the ISB reference frame in the sagittal plane was on average $\xi = 10.7^\circ$. The
214 difference between male and female for ξ was 0.6° and not statistically significant ($p = 0.6$,
215 Table 1).

216 **3.2 Alignment procedure**

217 All operators performed successfully the alignment, for all the specimens. The time
218 required was about 15 minutes for each specimen. The intra-operator repeatability was
219 generally below 1.5° for each angle (Fig. 6). The inter-operator reproducibility was less
220 than $\pm 2.0^\circ$ for each angle. Alignment in the transverse plane was most repeatable.

221 **4. DISCUSSION**

222 The aim of this study was to define a reference frame suitable for *in vitro* biomechanical
223 testing of the human pelvis, based on robust anatomical landmarks. As *in vitro* tests are
224 often performed on hemipelvises, the procedure was devised for a hemipelvis (rather than
225 relying on a whole pelvis). To enable comparisons and registrations with other studies,
226 the alignment with respect to a reference frame commonly used in movement analysis was
227 measured. Finally, we aimed at evaluating the reliability of the protocol in terms of intra-
228 operator repeatability and inter-operator reproducibility.

229 The alignment protocol revolved around anatomical landmarks, which could be accurately
230 identified on the physical *in vitro* specimens. The analysis of 53 patients' CT scans
231 allowed identifying the average alignment of a hemipelvis based on the alignment of its
232 original whole pelvis. No significant differences were detected between right and left
233 sides and between male and female specimens. Furthermore, the relative alignment of the
234 newly proposed *in vitro* reference frame for the hemipelvis was measured with respect to a
235 reference frame commonly used in gait analysis⁴. Thus, even if the rationale of this study
236 drove us to choose a different reference frame, it is possible to refer our *in vitro* frame to
237 the one used in gait analysis.

238 When the landmarks were identified *in silico* on CT scans, the intra-operator repeatability
239 was 0.5° in the frontal plane, and 0.5° in the transverse plane; the inter-operator
240 reproducibility was 2.6° in the frontal plane and 3.8° in the transverse plane. When the
241 alignment procedure was applied to physical hemipelvises *in vitro*, the intra-operator
242 repeatability was generally below 1.5° , and the inter-operator reproducibility was less than
243 $\pm 2.0^\circ$. The variability mainly depends on the uncertainty in the identification of the
244 landmarks. Due to the limited resolution of the CT scans, it is not surprising that the
245 uncertainty of the *in silico* alignment was worse than the *in vitro* one.

246 Past studies, where a reference frame was defined for other bone segments (tibia ⁶, and
247 vertebra ⁵), reported errors of the order of 1° - 3° , comparable to the present one. Only few
248 studies expressly defined a reference frame for the human pelvis *in vitro* ^{22-26; 31; 38}.

249 Comparisons with the present study are difficult, as the reproducibility of such references
250 has only seldom been quantified. For instance, Anderson *et al.* performed an *in vitro*
251 alignment of a whole pelvis based on the ASIS and pubic symphysis: while they focused
252 on relative rotations, they did not report the accuracy of their original alignment ³⁹. A
253 reference frame based on the acetabular plane is often adopted for *in vitro* purposes ^{24-26;}
254 ³¹. However, identification of this plane is complex due to the irregular shape of the
255 acetabular rim ^{32; 33}. To overcome this problem, we defined the alignment for a standard
256 acetabular plane (SAP) based on the advice of a group of hip surgeons.

257 To the Authors' knowledge, this is the second study in which a reference frame for the
258 hemipelvis was derived from the reference frame of the whole pelvis. In fact, van Arkel *et*
259 *al.* developed a procedure to apply the ISB reference frame to the whole pelvis before
260 bisecting it, and then apply the same reference when the hemipelvises were used for *in*

261 *vitro* testing^{4;22}. They found that after bisection, the hemipelvis had a misalignment
262 compared to the original whole pelvis. The error was $1.5\pm 1.6^\circ$ for the adduction, $0.5\pm 1.1^\circ$
263 for the internal rotation, and $0.6\pm 1.7^\circ$ for the flexion. However, as this error does not
264 include the intra- and inter-operator uncertainty in identifying the landmarks and initially
265 aligning the whole pelvis, the resultant total error of their procedure is larger (i.e. the sum
266 of such errors, and of the uncertainties in aligning the whole pelvis). Furthermore, for
267 some applications it might be preferable not to drill the large screw holes required to hold
268 the specimen during bisection²².

269 The main limitation of our approach is probably that, in order to standardize the reference
270 frame, and to be able to implement it on isolated hemipelvises, we were forced to make a
271 number of simplifications such as applying to any specimen the same average values of
272 the angles. We assumed that the anterior pelvic plane was vertical. However, the inter-
273 subject variability has been reported due to patient's anatomy and pose (i.e. when
274 changing from supine to standing position)^{40;41}. Consistently with our aim of
275 standardizing the alignment procedure, we assigned the alignment that corresponds to the
276 average reported in the literature (around 0° ^{21;41;42}). Similarly, the alignment of the
277 standard acetabular plane was defined based on angle values agreed upon by a pool of
278 surgeons. In principle, the proposed alignment procedure can be implemented also with
279 different angles for the acetabular plane: one just needs to change the final couple of
280 rotations.

281 The procedure has been tested on synthetic models of the pelvis. To include the
282 variability, both male and female specimens were used. Such models provide detailed

283 anatomy, including the presence and shape of the landmarks. This allowed testing the
284 intra-operator repeatability and inter-operator reproducibility of the alignment procedure.

285 An *in vitro* implementation of a procedure to identify robust anatomical landmarks allows
286 objectively determine the reference points for the alignment. It is important to underline
287 that reproducibility and repeatability of an alignment procedure strongly depend on the
288 identification of the anatomical landmarks; hence practical rules to identify these
289 landmarks should be always taken in consideration for *in vitro* purposes. The reference
290 frame and alignment procedure developed can be applied each time a hemipelvic
291 specimen is studied, both *in vitro* and *in silico*. Furthermore, the proposed reference
292 frame can be easily registered to match a reference frame commonly used in gait analysis.
293 Moreover, the intra-operator repeatability and inter-operator reproducibility quantified in
294 the present study are sufficient for most *in vitro* applications. For these reasons, the
295 presented procedure to align hemipelvic specimens is sufficiently robust, standardized,
296 and accessible, hence can be easily replicated in other laboratories. The proposed
297 reference frame can therefore be assumed as a starting point for numerous pre-clinical *in*
298 *vitro* tests e.g. to test implant stability of acetabular reconstructions.

299

300 **APPENDIX I: Standard acetabular plane (SAP)**

301 To overcome the known uncertainties and limitations of defining the acetabular plane
302 based on the acetabular rim ³⁰, a *standard acetabular plane* was defined (SAP). Standard
303 values for acetabular inclination (45 degrees) and anteversion (20 degrees) were chosen
304 according to a pool of experienced hip surgeons. Both values are within the Lewinnek
305 “safe zone” (inclination = $40^{\circ} \pm 10^{\circ}$; anteversion = $15^{\circ} \pm 10^{\circ}$) ¹⁷, which represents the goal
306 for most surgeons during cup implantation ^{17; 19; 43; 44}. It was demonstrated that prosthesis
307 implanted within the “safe zone” better resist to dislocation and impingement ^{17; 45}.

308 The angles necessary to align the SAP horizontal were calculated combining the
309 alignment of the hemipelvis based on the whole pelvis, and the inclination and anteversion
310 of the SAP (Fig. 7):

- 311 • Rotation in a quasi-transverse plane:

$$312 \quad \Phi = \text{Acetabular anteversion} + \delta = 20^{\circ} + 31^{\circ} = 51^{\circ}$$

- 313 • Rotation in the frontal plane:

$$314 \quad \Omega = \text{Acetabular inclination} - \beta = 45^{\circ} - 35^{\circ} = 10^{\circ}$$

315 where:

- 316 • β and δ are the average values of the angles measured from the 53 CT scans, to
317 align the hemipelvis based on the whole pelvis (see Par. 3.1).
- 318 • Φ and Ω are the final angles to align the hemipelvis with the SAP horizontal.
- 319 • All values were rounded to the closest integer.

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325

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TABLES

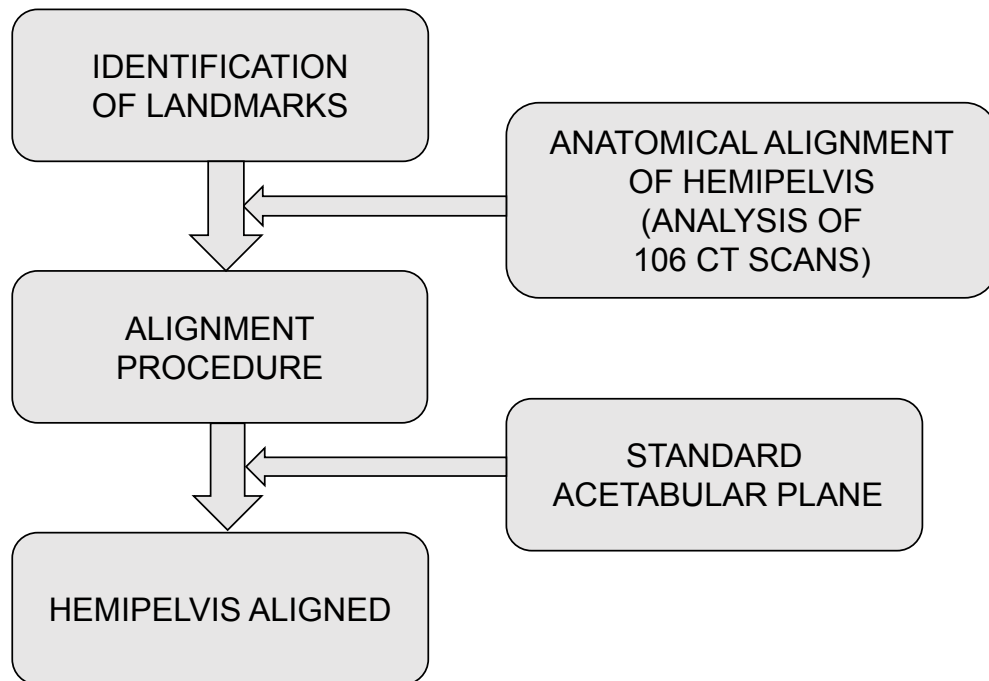
445 **Table 1** – Values of β , δ and ξ measured in the CT scans of 53 subjects (Fig. 3). Average
 446 and standard deviation are reported, after excluding outliers, for all subjects, and split by
 447 gender. The last column shows the average difference, and statistical significance
 448 (unpaired t-test).

Angles	All	Male	Female	Difference between Male and Female
β	$35.5^\circ \pm 4.0^\circ$	$35.2^\circ \pm 4.9^\circ$	$35.9^\circ \pm 2.6^\circ$	0.6° ($p=0.4$)
δ	$31.3^\circ \pm 3.8^\circ$	$31.4^\circ \pm 3.8^\circ$	$31.3^\circ \pm 3.9^\circ$	0.1° ($p=0.9$)
ξ	$10.7^\circ \pm 5.8^\circ$	$11.0^\circ \pm 6.2^\circ$	$10.3^\circ \pm 5.4^\circ$	0.6° ($p=0.6$)

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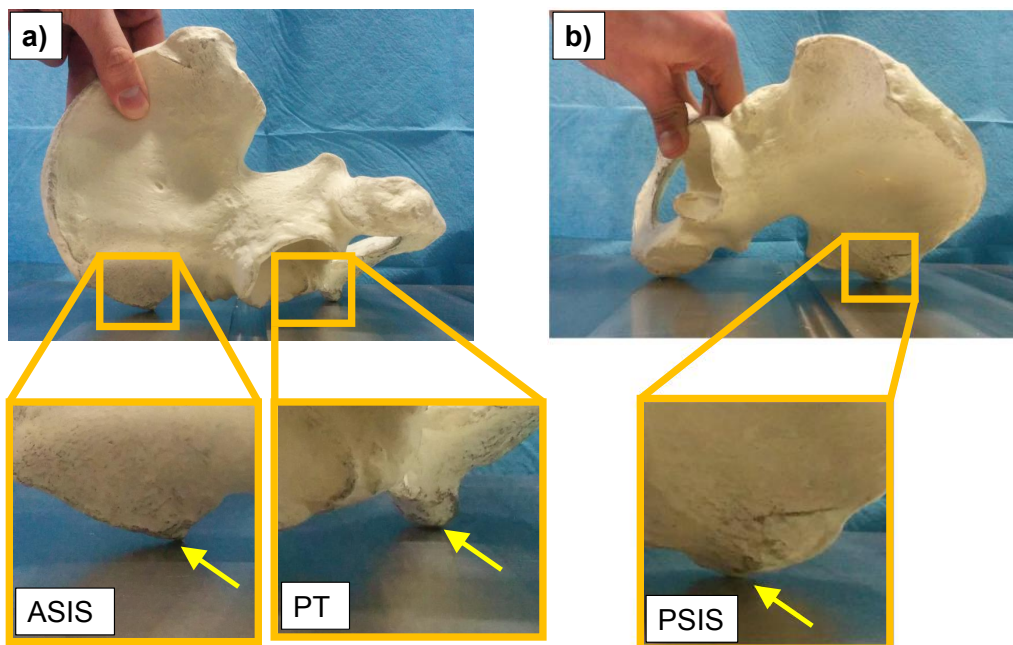
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451 **CAPTIONS TO FIGURES**



452

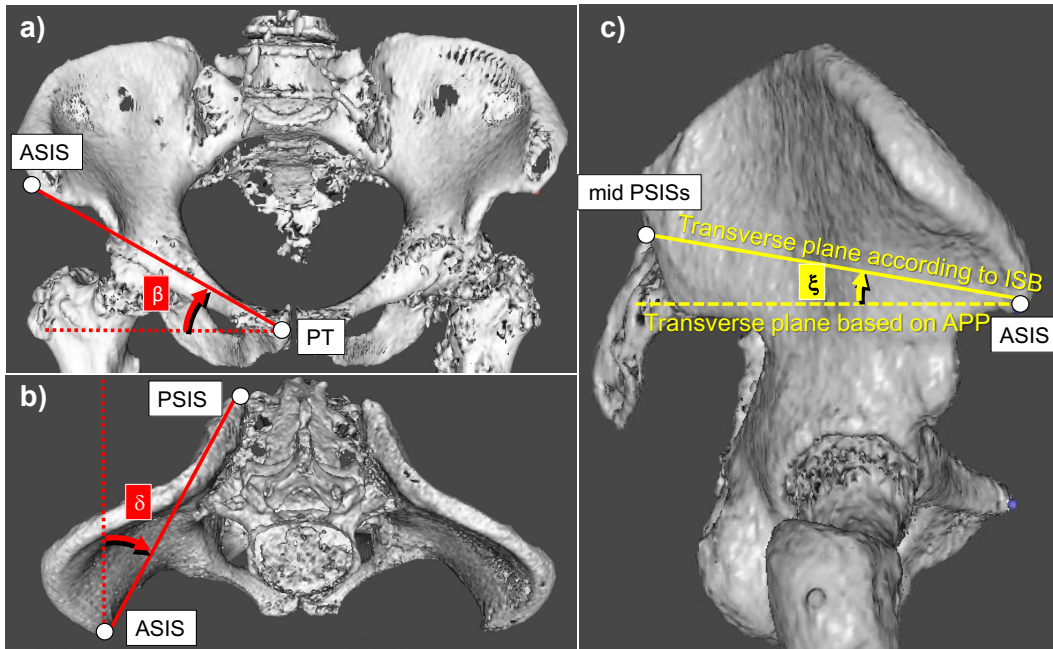
453 **Fig. 1** - Workflow of the proposed alignment procedure for the hemipelvis.



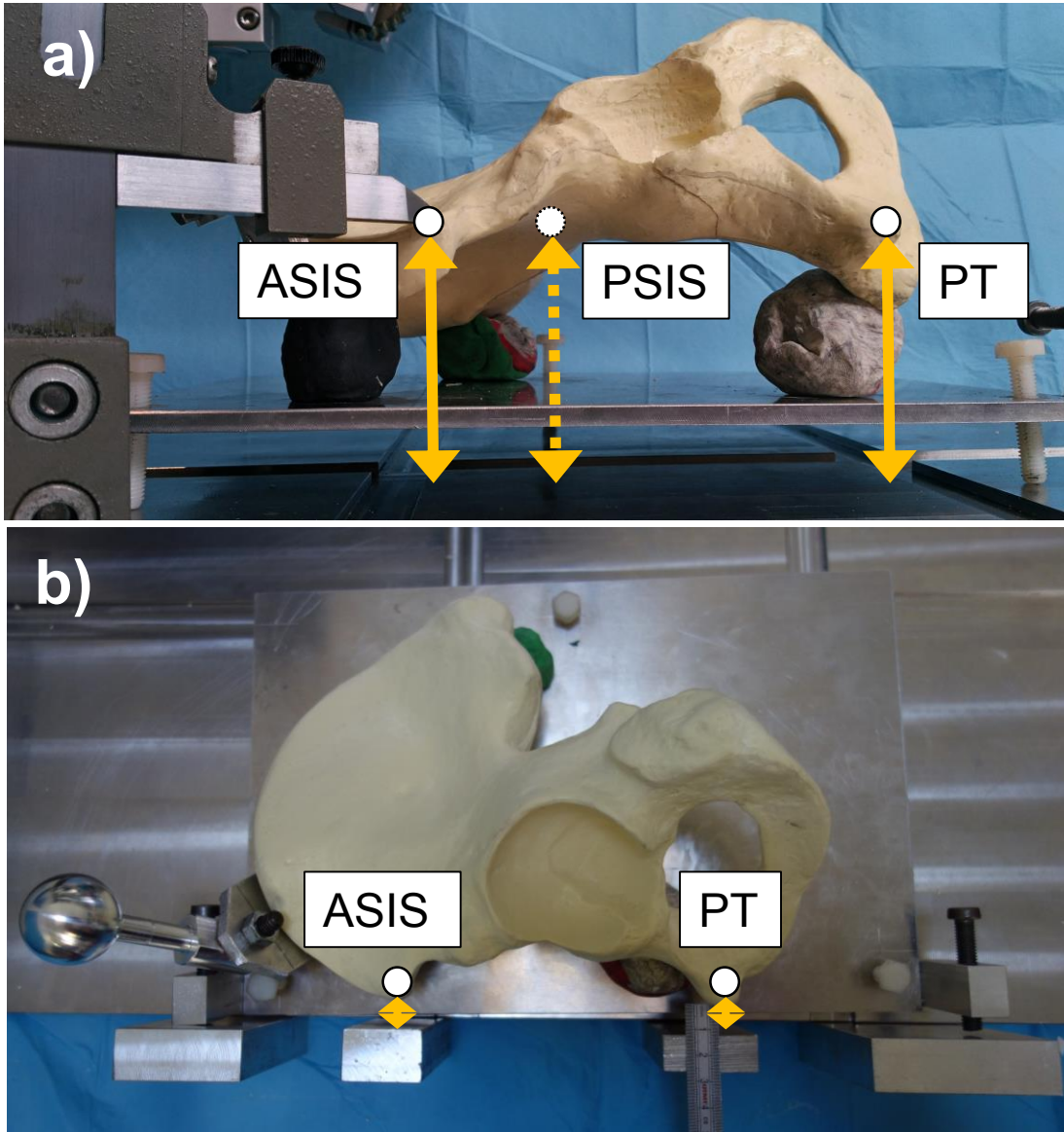
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455 **Fig. 2** – *In vitro* identification of the landmarks on a hemipelvis: a) ASIS and PT, b) PSIS.

456 A left specimen is shown in these pictures.

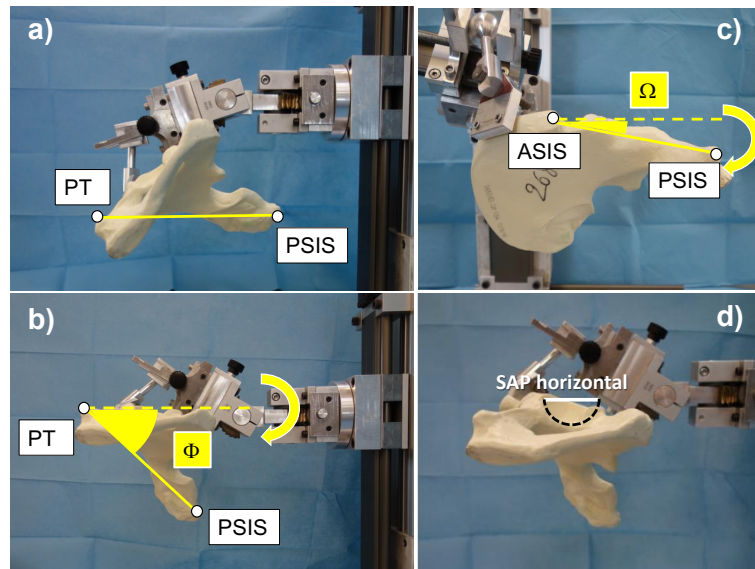


457
 458 **Fig. 3** - Three different angles were measured in the 53 patient CT scans using
 459 nmsBuilder. a) The angle (β) formed by the line connecting PT and ASIS with the
 460 transverse plane of the whole pelvis was measured in a frontal view. b) The angle (δ)
 461 formed by the line connecting ASIS and PSIS with the sagittal plane of the whole pelvis
 462 was measured in a transverse plane. c) The angle (ξ) between the proposed reference
 463 frame (based on the APP) and the ISB reference frame was measured in a lateral view.



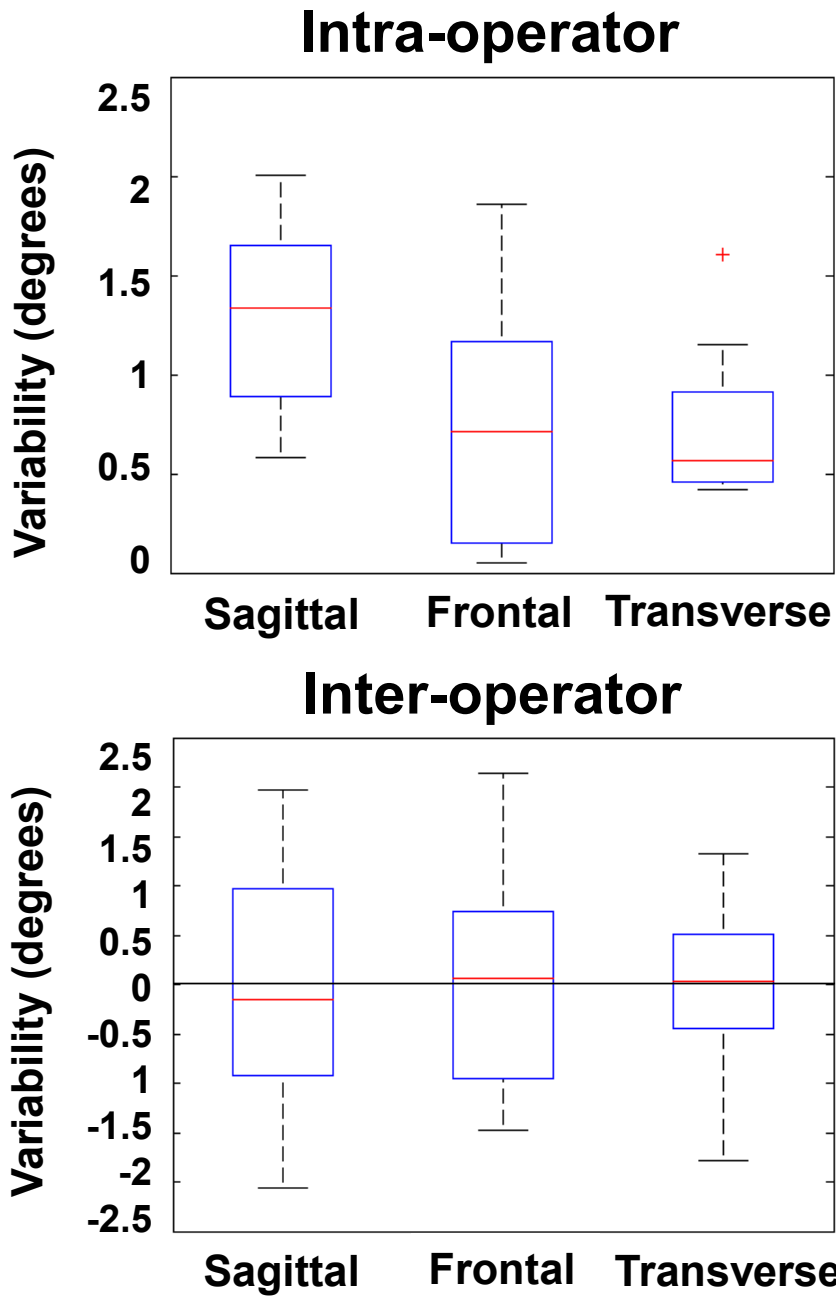
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465 **Fig. 4** – Alignment of a left hemipelvis: a) Vertical adjustment of the three landmarks.
 466 Quasi-frontal view, with the ASIS, PT and PSIS (hidden by the hemipelvis) at the same
 467 height, as measured with the vertical ruler (visible in the far left of the picture). Also
 468 visible is the spherical handle mounted on the hemipelvis. b) Horizontal adjustments of
 469 the landmarks. Lateral view of a left hemipelvis with ASIS and PT aligned with the edge
 470 of the reference plane.



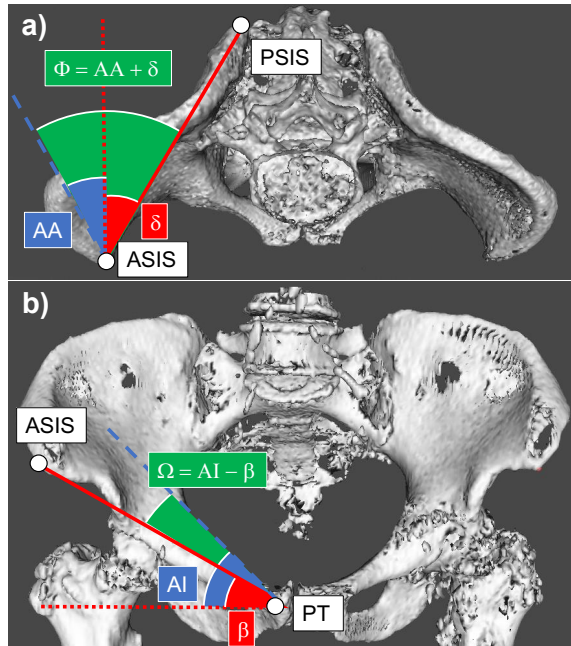
471

472 **Fig. 5** – Hemipelvis clamped in the 6-degrees of freedom manipulator through the handle
 473 rigidly fixed to the bone. a) Left hemipelvis viewed from distally (i.e. in a quasi-
 474 transverse plane) aligned as in Fig. 4, and lifted from the plane. b) Rotation of the
 475 specimen by Φ in the medial direction. c) Rotation of the specimen by Ω in the anterior
 476 direction. d) The standard acetabular plane (SAP) is horizontal once the specimen is
 477 aligned.



478

479 **Fig. 6** - Variability of measured angles on the hemipelvic specimens in each plane: intra-
 480 operator repeatability (top) and inter-operator reproducibility (bottom). The red mark
 481 indicates the median; the blue boxes includes the 25th –75th percentile; the whiskers extend
 482 to the most extreme data points. The outliers are marked with red crosses, and were
 483 excluded from the analysis.



484

485 **Fig. 7** – Combination of angles to align a hemipelvis with the standard acetabular plane
 486 (SAP) horizontal: (a) Top view of a CT scan of human pelvis showing the angle (Φ),
 487 which is calculated as the sum between the angle corresponding to the acetabular
 488 anteversion (AA) and δ ; (b) Frontal view showing the angle (Ω), which is calculated as the
 489 difference between the angle corresponding to the acetabular inclination (AI) and β .