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1 **Operative and Radiographic Acetabular Component Orientation in Total Hip**
2 **Replacement: Influence of Pelvic Orientation and Surgical Positioning Technique**

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46 **Abstract**

47 Orthopaedic surgeons often experience a mismatch between perceived intra-operative and
48 radiographic acetabular cup orientation. This research aimed to assess the impact of pelvic
49 orientation and surgical positioning technique on operative and radiographic cup orientation.

50 Radiographic orientations for two surgical approaches were computationally simulated: a
51 mechanical alignment guide and a transverse acetabular ligament approach, both in combination
52 with different pelvic orientations. Positional errors were defined as the difference between the
53 target radiographic orientation and that achieved.

54 The transverse acetabular ligament method demonstrated smaller positional errors for
55 radiographic version; $4.0^{\circ} \pm 2.9^{\circ}$ as compared to $9.4^{\circ} \pm 7.3^{\circ}$ for the mechanical alignment guide
56 method. However, both methods resulted in similar errors in radiographic inclination. Multiple
57 regression analysis showed that intraoperative pelvic rotation about the anterior-posterior axis
58 was a strong predictor for these errors ($B_{TAL} = -0.893$, $B_{MAG} = -0.951$, $p < 0.01$).

59 Application of the transverse acetabular ligament method can reduce errors in radiographic
60 version. However, if the orthopaedic surgeon is referencing off the theatre floor to control
61 inclination when operating in *lateral decubitus*, this is only reliable if the pelvic sagittal plane is
62 horizontal. There is currently no readily available method for ensuring that this is the case during
63 total hip replacement surgery.

64 **Keywords:** Pelvic Orientation; Mechanical Alignment Guide; Transverse Acetabular Ligament;
65 Acetabular component inclination

66 **1.0 Introduction**

67 Current survivorship of a primary total hip replacement (THR) exceeds 90% at ten years [1].
68 Despite this success, negative outcomes such as dislocation [2] and wear [3] persist. Mal-
69 alignment of the implanted acetabular component is one factor that has been implicated [3-5].
70 Great variability in acetabular component orientation is currently observed from post-operative
71 radiographs [6-8]. A number of factors contribute to this variation with the most important being
72 intra-operative pelvic orientation [9-10].

73 During THR, the acetabular component is inserted into the acetabulum using an introducer. The
74 acetabular component axis is usually co-linear with the handle of the introducer and
75 perpendicular to the face of the acetabular component being inserted. Acetabular component
76 orientation is currently defined in relation to this axis in terms of inclination and version for both
77 the operative and radiographic reference frames [11].

78 When using a mechanical alignment guide (MAG) in *lateral decubitus*, the operative inclination
79 is referenced off the theatre floor (as a surrogate for the pelvic sagittal plane) and operative
80 version is referenced from the surgical theatre table longitudinal axis (as a surrogate for the
81 anterior pelvic plane, APP). In reality, the APP is rarely parallel to the patient's coronal plane,
82 and the pelvic sagittal plane may not be parallel to the theatre floor as a result of pre-operative
83 patient positioning and intra-operative pelvic movement [9]. Angles referenced from external
84 theatre landmarks will, therefore, become *apparent* angles for operative inclination and version.
85 Discrepancies between *true* (relative to pelvic sagittal plane and APP) and *apparent* (relative to
86 theatre floor and table) operative acetabular component orientation will contribute to

MAG Mechanical Alignment Guide
TAL Transverse Acetabular Ligament
APP Anterior Pelvic Plane

A / TOI Apparent / True Operative Inclination
A / TOV Apparent/True Operative Version
NR I/V Neutralised Radiographic Inclination / Version

87 inconsistencies between the orthopaedic surgeon's expectations and the reality of post-operative
88 X-ray measurements when using a MAG approach.

89 The transverse acetabular ligament (TAL) has been used to determine a patient-specific operative
90 version relative to the APP [12]. TAL is independent of patient position but does not provide a
91 solution for operative inclination. To control operative inclination, TAL is often used with a
92 MAG or freehand approach. Pelvic mal-positioning and patient-specific TAL version will
93 contribute to radiographic variability when using this approach.

94 Post-operatively and intra-operatively there is significant variation in the orientation of the APP
95 with respect to the coronal plane of the patient [13]. This variation is commonly referred to as
96 anterior and posterior pelvic tilt. This tilt, or movement, occurs as a result of flexion or extension
97 of the lumbar spine which results in posterior and anterior tilt of the pelvis respectively. Because
98 the X-ray is taken normal to the patient's coronal plane, pelvic tilt impacts the angle of
99 radiographic version and, to a lesser degree, inclination [14]. Previous work [15-19] has analysed
100 the discrepancy between the 3D orientation (operative or CT) and radiographic orientation of the
101 acetabular component relative to the pelvis. However, the influence of surgical approach has not
102 been explicitly analysed in relation to operative and radiographic acetabular cup orientation.

103 The aim of this research was to assess the impact of surgical positioning technique on operative
104 and radiographic cup orientation for different pelvic orientations. Two different surgical
105 techniques were simulated using the theory of rigid body transformations. The first used the
106 surgical theatre table longitudinal axis to control operative version. This is equivalent to using
107 the "version guide" on a MAG. The second simulated surgical technique used the TAL. For
108 operative inclination, both techniques used the theatre floor. These approaches are the most
109 commonly adopted within the UK with more than 50% of orthopaedic surgeons using them

110 during THR [20]. Our hypothesis was that the TAL method would result in better control over
111 acetabular component positioning relative to the pelvis when compared to the MAG method.

112 **2.0 Method**

113 *2.1 Defining Acetabular Orientation*

114 Acetabular orientation has previously been defined by inclination and version for both the
115 operative and radiographic reference frames [11]. However, these definitions fail to take into
116 account pelvic orientation [11]. To account for the impact of pelvic orientation, this paper
117 proposes new definitions (Figures 1-3).

118 Apparent operative acetabular cup orientation is the orientation of the acetabular component axis
119 relative to external landmarks such as the surgical theatre floor and wall, intra-operatively, as
120 perceived by orthopaedic surgeons. **Apparent operative inclination** (AOI) was defined as the
121 angle between the acetabular component axis and the surgical theatre floor (Figure 1). **Apparent**
122 **operative version** (AOV) was defined as the angle between the acetabular component axis and
123 the surgical theatre table longitudinal axis as projected onto the surgical theatre floor (Figure 2).

124 True operative acetabular orientation represents the orientation of the acetabular component axis
125 relative to internal pelvic landmarks such as the APP intra-operatively. **True operative**
126 **inclination** (TOI) was defined as the angle between the acetabular component axis and the pelvic
127 sagittal plane (Figure 1). **True operative version** (TOV) was the angle between the acetabular
128 component axis and the APP as projected onto the pelvic sagittal plane (Figure 2).

129 Radiographic inclination and version are the measurements routinely referenced in practice that
130 do not take into account anterior and posterior pelvic tilt. **Radiographic inclination** (RI) was
131 calculated as the angle between the pelvic longitudinal axis and the acetabular component axis
132 projected onto the coronal plane (Figure 3) [11]. **Radiographic version** (RV) was determined

133 from the relative sizes of the minor and major diameters [21] of the projected acetabular
134 component face (Figure 3). *Neutralised radiographic* acetabular component orientation was
135 defined as the radiographic inclination (NRI) and version (NRV) that would result from an X-
136 ray for which the pelvis was neutral. Radiographic pelvic neutrality was achieved when the APP
137 was parallel to the coronal plane (Figure 3).

138 2.2 Intra-operative Pelvic Orientation

139 A Sawbones™ pelvis (Sawbones Europe AB, Sweden) was surface-scanned using a coordinate
140 measurement machine (Hexagon Global Status CMM 092008, Hexagon Manufacturing
141 Intelligence, UK) equipped with a Renishaw PH10M probe head (Renishaw plc, UK) and Nikon
142 LC50 Laser with Nikon Focus scan software (Nikon Corp., Japan) to produce a high density
143 point cloud, which was converted into a surface mesh using 3D scanning and computer aided
144 design (CAD) software (Rapidform XOR, 3D Systems Inc., USA and PTC Creo, PTC Inc., USA)
145 and imported into MATLAB (2015b, The MathWorks Inc., USA). The pelvic model was initially
146 orientated to match the idealised *neutral* pelvic orientation for a patient undergoing THR of a
147 left hip in *lateral decubitus*. Operative pelvic neutrality was achieved when the pelvic APP was
148 parallel to the surgical theatre table longitudinal axis, and the pelvic sagittal plane was parallel
149 to the surgical theatre floor.

150 Coordinates for the hip joint centre of rotation (\hat{c}_N ; COR) relative to a neutral pelvis in the
151 operative reference frame were acquired (Figure 4). Rotation of the neutral pelvis about its three
152 axes (Figure 4) was achieved using Equation 1. Regardless of approach, the rotated position of
153 the hip COR (\hat{c}_R) represents the pivot about which the orthopaedic surgeon orientates the
154 acetabular component. Rotation of the upper (left) hemi-pelvis about its longitudinal axis,
155 $R_x(\theta_{rot})$, intra-operatively was regarded as internal (+) / external (-) rotation. Rotation of the
156 upper (left) hemi pelvis about its anterior-posterior axis, $R_y(\theta_{add})$, was regarded as abduction

157 (+) / adduction (-). Rotation of the pelvis about its transverse axis, $R_z(\theta_{\text{tilt}})$, intra-operatively
 158 was termed anterior (+) / and posterior (-) pelvic tilt.

$$159 \quad \hat{\mathbf{c}}_R = \mathbf{R}_x(\theta_{\text{rot}})\mathbf{R}_z(\theta_{\text{add}})\mathbf{R}_y(\theta_{\text{tilt}})\hat{\mathbf{c}}_N \quad \text{Eqn. 1}$$

160 *2.3 Mechanical Alignment Guide Approach*

161 With the pelvis mal-rotated, the acetabular component axis was angled at 45° relative to the
 162 theatre floor (AOI) and 20° relative to the long axis of the surgical theatre table as projected onto
 163 the surgical theatre floor (AOV) [10,21-22]. This was achieved by rotating the acetabular
 164 component relative to the axes of its local coordinate frame ($\hat{\mathbf{e}}_1$, $\hat{\mathbf{e}}_2$ and $\hat{\mathbf{e}}_3$, Figure 4). The surgical
 165 error (i.e. the orthopaedic surgeon's ability to achieve their target orientation) when using the
 166 MAG approach was also incorporated. The surgical errors for version (SE_{MAGV} , $3 \pm 5^\circ$) and
 167 inclination (SE_{MAGI} , $-3 \pm 5^\circ$) were based on an assumed normal distribution defined by mean
 168 and standard deviation error values from an experimental study of surgical accuracy [23]. The
 169 resultant position of the acetabular cup axis for the MAG approach ($\hat{\mathbf{i}}_M$) was obtained using
 170 Equation 2, which orientated the introducer such that it matched Murray's definitions for
 171 operative acetabular orientation.

$$172 \quad \hat{\mathbf{i}}_M = (\mathbf{R}_y(-AOV + SE_{\text{MAGV}})\mathbf{R}_z(AOI + SE_{\text{MAGI}})\hat{\mathbf{e}}_1) + \hat{\mathbf{c}}_R \quad \text{Eqn. 2}$$

173 *2.4 Transverse Acetabular Ligament Approach*

174 For the TAL approach, a TAL axis was introduced relative to the neutral pelvis ($\hat{\mathbf{t}}_N$; Figure 5).
 175 This axis was assigned a case-specific TAL version (TOV) and surgical error (SE_{TALV}), Equation
 176 3. The location of the TAL axis relative to the mal-rotated intra-operative pelvis ($\hat{\mathbf{t}}_R$) was
 177 obtained using Equation 4.

$$178 \quad \hat{\mathbf{t}}_N = (\mathbf{R}_y(-TOV + SE_{\text{TALV}})\hat{\mathbf{e}}_3) + \hat{\mathbf{c}}_N \quad \text{Eqn. 3}$$

$$179 \quad \hat{\mathbf{t}}_R = \mathbf{R}_x(\theta_{\text{rot}})\mathbf{R}_z(\theta_{\text{add}})\mathbf{R}_y(\theta_{\text{tilt}})\hat{\mathbf{t}}_N \quad \text{Eqn. 4}$$

180 With the pelvis and consequently the TAL axis mal-rotated, the acetabular component axis was
 181 angled at 45° relative to the surgical theatre floor (AOI) about the TAL axis. A custom solver,
 182 Equation 5, was developed to determine the angle (α) that the acetabular cup axis for the TAL
 183 method ($\hat{\mathbf{i}}_T$) would have to rotate about the $\hat{\mathbf{i}}_R$ axis to provide an AOI of 45°, between the
 184 introducer and theatre floor ($\hat{\mathbf{i}}_{Txz}$; Figure 5). Surgical errors for the TAL method (SE_{TALI} , $-3 \pm$
 185 5° , and SE_{TALV} , $0 \pm 7^\circ$) were based on the findings of Grammatopoulos et al [23]. This in turn
 186 provided the resultant intra-operative location of the acetabular cup axis when using the TAL
 187 approach ($\hat{\mathbf{i}}_T$).

$$188 \quad f(\alpha) = (AOI + SE_{TALI}) - \cos^{-1}(\hat{\mathbf{i}}_T \cdot \hat{\mathbf{i}}_{Txz}) \quad \text{Eqn. 5}$$

189 *2.5 Analysis*

190 Measures for apparent operative, true operative, radiographic, and neutralised radiographic
 191 acetabular orientation were obtained from the model. Variation in TAL version [24], surgical
 192 error [23] and pelvic orientation [9] were incorporated into the models to induce variation in the
 193 aforementioned measures. For each factor, normal distributions were fitted to clinical data from
 194 the literature and sampled randomly ($n = 1,000$). Since one of the main consequences of sub-
 195 optimal acetabular cup positioning (dislocation) is relatively rare, a large sample size was
 196 required in order to include extreme cases. Radiographic projection was modelled according to
 197 Freud et al. [25] with a source-to-image distance of 1 m. For repeatability, the source was aligned
 198 with the pubic symphysis of the pelvic model whilst the rearmost portion of the pelvic model
 199 was aligned with the image plane. As the rearmost portion of the pelvis is aligned with the image
 200 plane (supported by the table in practice), if the pelvic tilt changes, the distance between the
 201 pubic symphysis and the source would change (as would occur in surgical practice). Therefore
 202 there is not a single fixed distance between the pelvis and the source. Target radiographic
 203 orientation was the neutralised radiographic orientation that would have been achieved if the

204 acetabular component had been implanted into a neutral pelvis intra-operatively in the absence
205 of surgeon error. A case was classified as on-target if its neutralised radiographic orientation was
206 within 10° of the target radiographic orientation, based on ranges presented by Lewinnek et al
207 [21]. For each case, a positional error was calculated. This was defined as the difference between
208 the neutralised radiographic orientation achieved and the target radiographic orientation.
209 Multiple linear regression, general mixed models, and Chi Square analyses were conducted using
210 SPSS (v22, IBM, USA). Multiple linear regression was used to determine the relationship
211 between positional errors and surgical factors. General mixed models with Bonferroni post-hoc
212 analysis were used to test for statistical differences between measures of orientation. Chi Square
213 analysis was conducted to determine if there was a significant interaction between safe placement
214 and the choice of guidance technique. Further analysis was conducted using the Statistics
215 Toolbox and plotting capabilities within MATLAB® (2015b, The Mathworks Inc., USA). A p-
216 value of 0.05 was considered significant.

217 **3.0 Results**

218 **3.1 Inclination**

219 No statistical difference ($p = 0.243$) was observed between the TAL and MAG methods across
220 the measures of inclination (Figure 6). However, each of the four measures for inclination were
221 mutually statistically different from each other ($p < 0.001$). Despite statistical significance, there
222 was negligible difference between the mean AOI and TOI (MAG = 0.5° , TAL = 0.8° ; Table 1).
223 The same was true of the difference between the mean RI and NRI (MAG = 1.1° , TAL = 1.1°).
224 Regardless of the small deviation in the mean angle of inclination across all measures, there was
225 an initial increase in the ranges between AOI ($\Delta\text{AOI}_{\text{MAG}} = 20.4^\circ$, $\Delta\text{AOI}_{\text{TAL}} = 20.4^\circ$) and TOI
226 groups ($\Delta\text{TOI}_{\text{MAG}} = 40.9^\circ$, $\Delta\text{TOI}_{\text{TAL}} = 45.2^\circ$). Despite an orthopaedic surgeon's level of control
227 over the orientation of the introducer relative to the surgical theatre floor, these results indicate

228 that intra-operative pelvic orientation can double the range in inclination that an orthopaedic
229 surgeon would expect to see post-operatively.

230 **3.2 Version**

231 Unlike inclination, a statistical difference ($p < 0.001$) was observed between the TAL and MAG
232 methods across measures of version (Figure 7). For AOV, the MAG method exhibited tighter
233 control ($\Delta\text{AOV}_{\text{MAG}} = 21.7^\circ$) when compared to the TAL method ($\Delta\text{AOV}_{\text{TAL}} = 106.7^\circ$). Despite
234 this apparent increase in control, the TAL method ($\Delta\text{TOV}_{\text{TAL}} = 50.1^\circ$) results in a smaller range
235 of TOV when compared to the MAG method ($\Delta\text{TOV}_{\text{MAG}} = 103.2^\circ$). Linear regression showed
236 the variability in TOV is predominantly accounted for by the variation in the natural target TAL
237 version ($r = 0.75$, $p < 0.01$). From the orthopaedic surgeon's perspective, the angular orientation
238 of the acetabular component may appear excessive when using the TAL method. However, as
239 indicated by the reduction in TOV over AOV, the TAL method results in better control over
240 operative version.

241 AOV and TOV were considered statistically similar ($p = 0.243$), while the other measures were
242 all mutually statistically different ($p < 0.001$). The introduction of anterior and posterior pelvic
243 tilt alters the angle of version projected onto the coronal plane, accounting for differences
244 between the operative measures of version and the radiographic version. Deviations between the
245 mean TOV (MAG = 16.5° , TAL = 17.9°) and the mean NRV (MAG = 8.82° , TAL = 10.1°)
246 reflect the inadequacy of the ellipse fitting method used to compute the three-dimensional
247 version of the acetabular component from a two-dimensional radiograph.

248 **3.3 Positional Errors**

249 Target radiographic inclination and version for the MAG method was 47.8° and 10.6°
250 respectively when aiming for 45° of operative inclination and 20° of operative version. Due to

251 the natural variation in TAL-based version, target radiographic inclination and version were
252 case-specific for the TAL method even though target operative inclination was constant. Mean
253 target radiographic inclination for the TAL method was $47.8^\circ (\pm 1.52^\circ, \text{min} = 45.1^\circ, \text{max} = 52.2^\circ)$.
254 Mean target radiographic version for the TAL method was $9.96^\circ (\pm 4.46^\circ, \text{min} = 0.02^\circ, \text{max} =$
255 $20.1^\circ)$. Target radiographic inclination ($n = 104/1,000$) and radiographic version ($n = 148/1,000$)
256 for a number of TAL cases fell outside of the Lewinnek target zone²⁰ (Figures 6 and 7). Thus,
257 acetabular components may be classified as unsafe when using the Lewinnek target zone, despite
258 being placed inside the allowable margin of error ($\pm 10^\circ$) relative to their intended orientation.

259 A Chi-square test of independence was calculated comparing the frequency of acetabular
260 components placed safely when using the TAL and MAG method. A significant interaction was
261 found ($\chi^2(1, n = 1,000) = 150.3, p < 0.01$) between insertion methods and safe placement. With
262 respect to placement within the safe zones for both radiological inclination and version, the TAL
263 method ($n = 778/1,000$) exhibited a 33.7% increase in safe placement over the MAG method (n
264 $= 516/1,000$).

265 For inclination error (Figure 8, Table 2), multivariate linear regression showed that the strongest
266 standardised coefficients (B), or predictors, were the orthopaedic surgeon's ability to achieve
267 their desired target angle ($B_{\text{MAG}} = 1.02, B_{\text{TAL}} = 1.10, p < 0.01$) and intra-operative control of
268 pelvic adduction ($B_{\text{MAG}} = -0.95, B_{\text{TAL}} = -0.89, p < 0.01$) for both MAG and TAL (Figure 8,
269 Table 2). For errors in version, the orthopaedic surgeon's ability to achieve their desired target
270 angle ($B_{\text{MAG}} = 0.711, p < 0.01$) and intra-operative control of pelvic flexion were the strongest
271 predictors ($B_{\text{MAG}} = 0.689, p < 0.01$) for MAG. For TAL, only the orthopaedic surgeon's ability
272 to achieve their desired target angle ($B_{\text{TAL}} = 0.708, p < 0.01$) was a notable predictor of version
273 error.

274

275 **4.0 Discussion**

276 We hypothesised that the TAL method would result in better control over acetabular component
277 positioning relative to the pelvis when compared to the MAG method. The TAL method (ΔTOV
278 = 50.0°) resulted in a smaller range of TOV when compared to the MAG method (ΔTOV =
279 103.2°). However, for TOI, the TAL method (ΔTOI = 45.3°) exhibited similar variability to the
280 MAG method (ΔTOI = 41.0°). The TAL method uses a fixed internal patient-specific landmark
281 for controlling operative version, which can counteract changes in pelvic tilt. However, as with
282 the MAG method, it relies on the fixed external surgical theatre floor for controlling operative
283 inclination. Overall, our hypothesis that the TAL method would lead to better control over
284 acetabular component orientation was supported by the results herein.

285 For both methods, intra-operative pelvic orientation at least doubled the range in inclination that
286 an orthopaedic surgeon would expect to see post-operatively. This is particularly influenced by
287 pelvic adduction. However, high natural cup version combined with internal rotation can also be
288 a contributing factor. Therefore, in *lateral decubitus*, the surgical theatre floor can only be used
289 as a reliable landmark for operative inclination if the sagittal plane of the pelvis is horizontal.

290 Meermans et al.²⁶ conducted a clinical trial comparing the TAL and freehand techniques. From
291 their findings, the TAL method was better at controlling radiological version than the MAG
292 technique, which concurs with the findings from this study. The range in measured radiological
293 version obtained using our theoretical model (MAG: -35.5° to 37.4° , TAL: -24.4° to 30.1°)
294 differs from that obtained by Meermans et al in a clinical setting (MAG: 2° to 35° , TAL: 2° to
295 25°). An advantage of the theoretical model is the spatial location of the acetabular component
296 axis relative to the radiographic coronal plane is known. This enables differentiation between
297 retroverted and anteverted acetabular components, which is not possible on the AP X-ray.
298 Ignoring the possibility of retroversion by taking the absolute values of measured radiographic

299 version only, the ranges obtained from the theoretical model (MAG: 0° to 37.4°, TAL: 0° to
300 30.1°) concurs with data reported by Meermans et al [26].

301 Meermans et al. [26] concluded that the TAL method was better at controlling radiological
302 version based upon their radiographic outcomes being within the Lewinnek target zone.²¹ Natural
303 variation of TAL, [23] along with the natural variation in pelvic tilt, [13] may result in greater
304 inter-patient variability with respect to measured radiological version. In this study, patient-
305 specific targets for NRI and NRV were calculated. With respect to the Lewinnek target zone
306 [21], 43% (n = 430/1000) of target neutralised radiographic orientations fell outside for TAL.
307 Other studies have also noted potential problems with using global, rather than patient-specific,
308 targets; e.g. Abdel et al. [6] illustrated that 58% of dislocations from their prospective study were
309 located within the Lewinnek target (safe) zone. To date, no consensus regarding safe orientation
310 of the acetabular component exists [2,8,27]. Irrespective of the safe zone used to assess
311 radiographic success post-operatively, TAL has been associated with a reduced rate of
312 dislocation [12].¹²

313 A potential limitation of this study is the use of a single order of rotations. However, the same
314 pelvic orientation can result from differently ordered rotations. Thus, changing the order of the
315 rotations only varies the mapping procedure required to gain a particular pelvic orientation. If
316 we were to include multiple mappings, duplicate pelvic positions would result, which may bias
317 the data and subsequent observations from this study. A limitation of the theoretical model was
318 that it was based on clinical data from a limited number of institutions [9,23,24]. For example,
319 the extent of pelvic mal-positioning may be influenced by the type of intraoperative patient
320 support. Additionally, in practice, an orthopaedic surgeon will be able to use their experience to
321 avoid extreme orientations that are not accounted for in the model. This study was performed on
322 a single, representative pelvic shape. Since the key variables are angles (as opposed to lengths),

323 we expect that data and study observations will apply to a wide variation of pelvic shapes.
324 However, this has not been analysed here and these methods could be applied in future studies.

325 Computer Aided Orthopaedic Surgery (CAOS) has been shown to reduce the variance in
326 acetabular component placement²⁸ by determining the intra-operative pelvic orientation. This is
327 most accurately achieved using an image-based system that recognises the internal anatomy
328 during THR surgery and then builds a three-dimensional image of the pelvis from this. In
329 contrast, image-free systems are more widely used to build a three-dimensional image by
330 referencing bony landmarks on the pelvis through skin, which in turn introduces errors.²⁹ Within
331 the United Kingdom, CAOS is used in less than 1% of THR surgeries [30]. This may be due to
332 cost, increased operative time, and lack of published benefit [31,32]. For example, Lass et al.
333 [33] illustrated no significant difference between the MAG method and an image free system for
334 controlling TOI.

335 **5.0 Conclusion**

336 In this study, which simulated two different surgical techniques, the TAL method exhibited
337 greater control over radiographic version and placed 33.7% more acetabular components in the
338 hypothetical target zone when compared to the application of the MAG method. However, with
339 respect to inclination, both the TAL and MAG methods performed poorly when the sagittal
340 pelvic plane was not parallel to the surgical theatre floor. Consequently, there is an imperative
341 to find an affordable and practical method to ensure the sagittal plane of the pelvis is parallel to
342 the surgical theatre floor at the time of acetabular component insertion.

343

344 **Conflicts of interest**

345 There are no conflicts of interest.

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350 **Ethical approval**

351 No ethical approval was required for this study.

352

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444 Table 1. Minimum, maximum, mean, and standard deviation for inclination and version measures for the MAG and TAL method.

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	Mechanical Alignment Guide (MAG)				Transverse Acetabular Ligament (TAL)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)
AOI	28.6	49	41.4	4.2	28.6	49	41.4	4.2
TOI	22.1	63.1	41.9	7.1	19.2	64.5	42.2	7.8
RI	22.3	66.2	44.2	7.6	18.5	65.1	43.9	7.6
NRI	22.7	71.4	45.3	7.9	20.2	67.4	45	7.5
PI*	0	25	6.6	5	0	27.6	6.4	5
AOV	2.2	23.9	16.1	4.4	-34.8	71.9	17.7	19
TOV	-40.6	62.6	16.5	16.8	-8.7	41.3	17.9	9.3
RV	-35.5	37.4	3.8	12.6	-24.4	30.1	5.1	8.5
NRV	-32.1	44	8.8	11.8	-9.1	35.2	10.1	7
PV*	0	42.7	9.4	7.3	0	17.4	4	2.9

455 *PI: Absolute positional error in inclination

456 *PV: Absolute positional error in version

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458 Table 2. Prediction of inclination positional errors (PI) and version positional errors (PV) from intra-operative factors using multivariate regression
 459 standardised coefficients (B).

		Mechanical Alignment Guide (MAG)		Transverse Acetabular Ligament (TAL)	
Predictor		B	<i>p</i>	B	<i>P</i>
PI	Constant (Intercept)	1	<0.001	0.832	<0.001
	Operative Pelvic Rotation	0.24	<0.001	0.273	<0.001
	Operative Pelvic Adduction	-0.951	<0.001	-0.893	<0.001
	Operative Pelvic Flexion	0.198	<0.001	0.157	<0.001
	Surgeon Inclination Error	1.024	<0.001	1.1013	<0.001
	Model Fit	F(4, 995) = 4,379, $p < 0.001$, $R^2 = .946$		F(4, 995) = 2,451, $p < 0.001$, $R^2 = .908$	
PV	Constant (Intercept)	0.925	<0.001	0.831	<0.001
	Operative Pelvic Rotation	-0.626	<0.001	-0.09	<0.001
	Operative Pelvic Adduction	-0.016	0.105	0.245	<0.001
	Operative Pelvic Flexion	0.689	<0.001	-0.046	<0.001
	Surgeon Version Error	0.711	<0.001	0.708	<0.001
	Model Fit	F(4, 995) = 10,678, $p < 0.001$, $R^2 = .977$		F(4, 995) = 1,584, $p < 0.001$, $R^2 = .864$	

460

Figures

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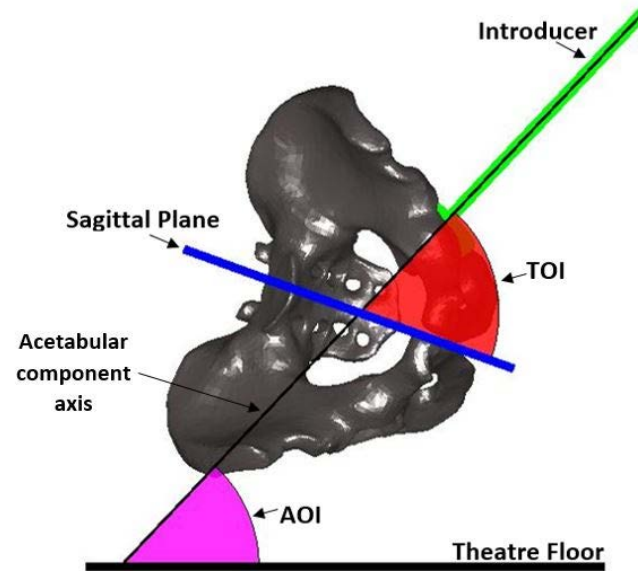
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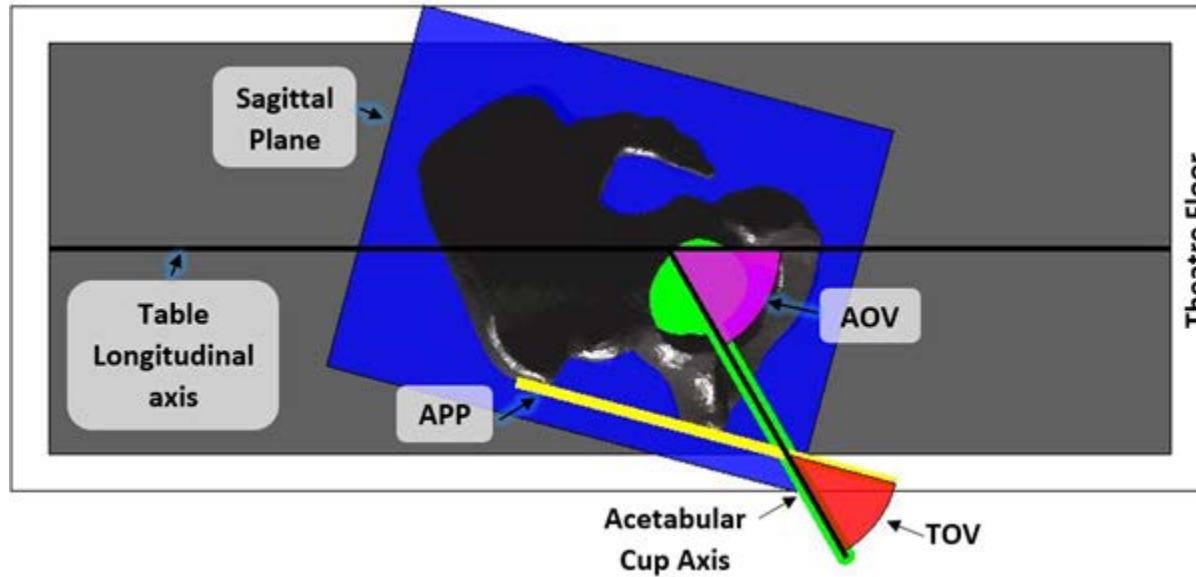
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469 Figure 1: Apparent (AOI) and True Operative Acetabular Inclination (TOI). TOI is the angle between the acetabular component axis and the pelvic
470 sagittal plane. AOI is the angle between the acetabular component axis and the surgical theatre floor.

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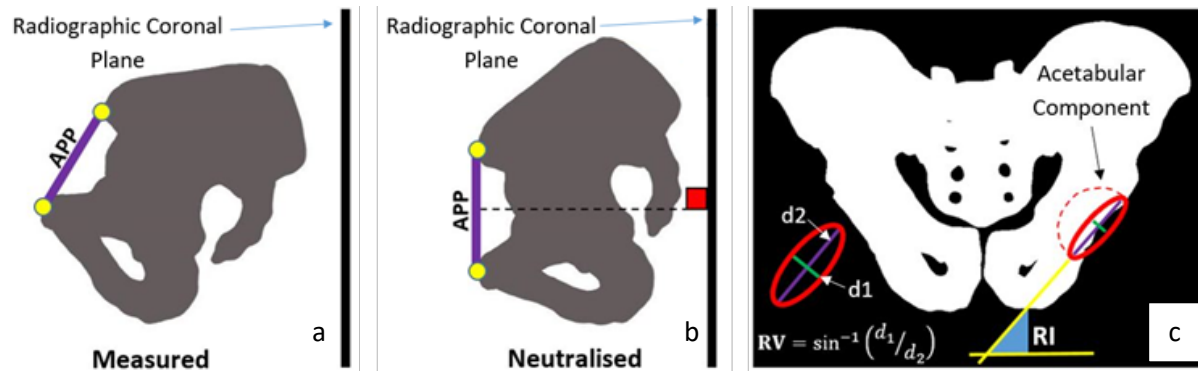


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473 Figure 2: Apparent (AOV) and True Operative Acetabular Version (TOV). AOV is the angle between acetabular component axis and surgical
 474 theatre table longitudinal axis as projected onto the surgical theatre floor. TOV is the angle between the acetabular component axis and anterior
 475 pelvic plane (APP) as projected onto the pelvic sagittal plane.

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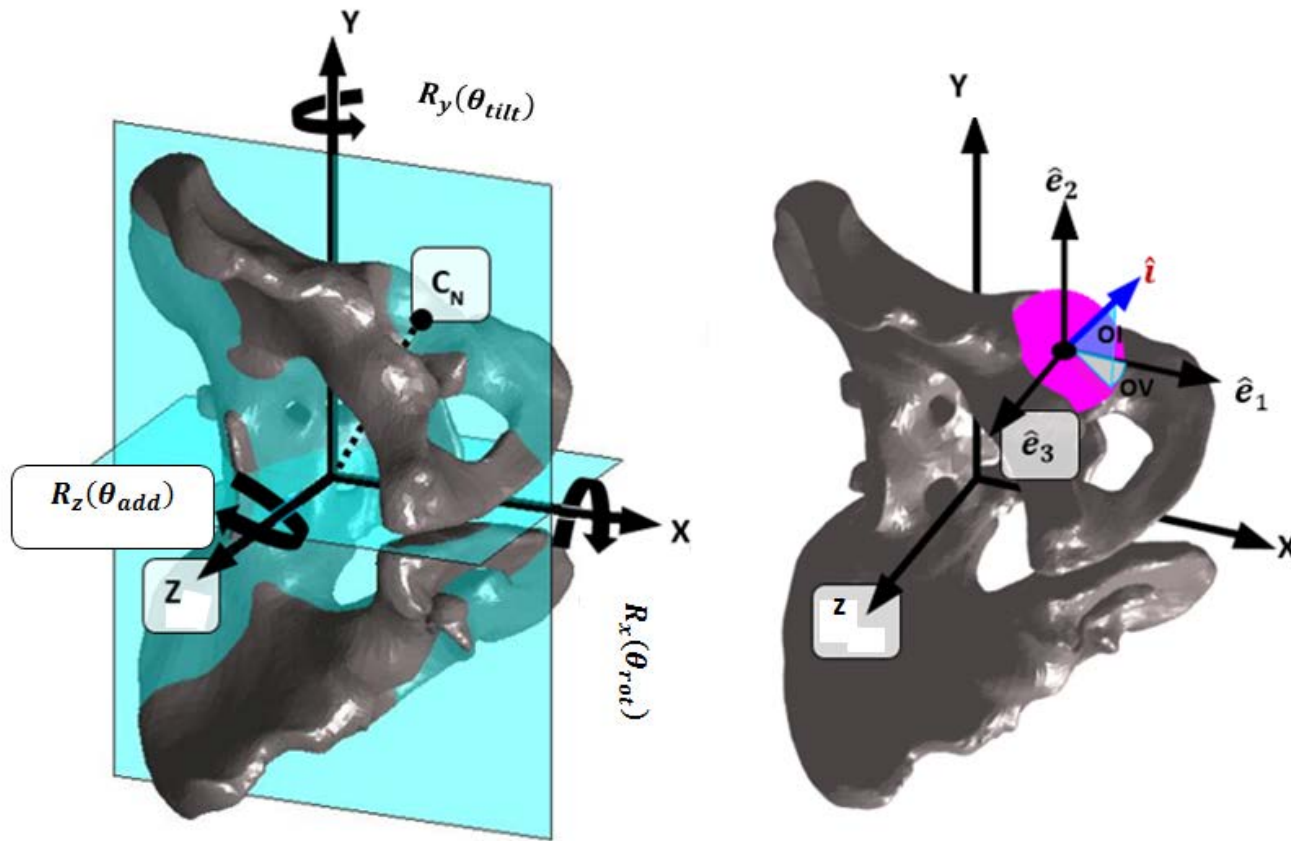
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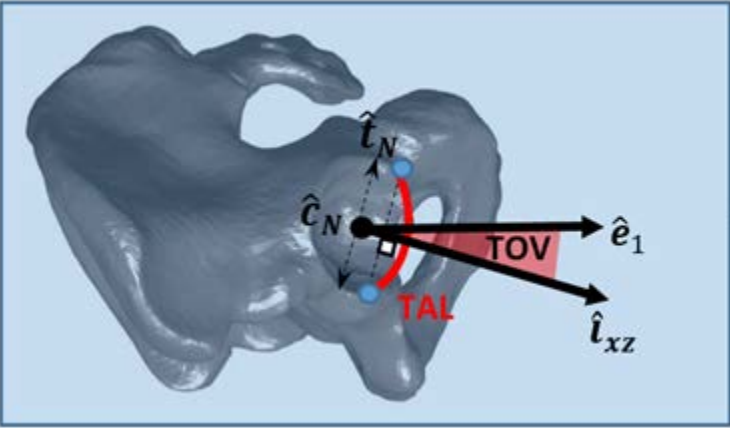
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479 Figure 3: Measured and Neutralised Radiographic Measurements: a & c) radiographic inclination (RI) and Version (RV) are measures of inclination
 480 and version taken from an anterior-posterior radiograph for which the orientation of the pelvis has not been accounted for; b & c) neutralised
 481 radiographic inclination (NRI) and version (NRV) are measures of radiographic inclination and version taken from an anterior-posterior radiograph
 482 for which the orientation of the pelvis *has* been accounted for.

483



492 Figure 4: Schematic diagram highlighting the pelvic (X,Y,Z) and acetabular cup ($\hat{e}_1, \hat{e}_2, \hat{e}_3$) coordinate frames, the hip joint centre of rotation (\hat{C}_N),
 493 and acetabular cup axis (\hat{i}).



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Figure 5: Schematic diagram depicting a neutral transverse acetabular ligament (TAL) axis (\hat{t}_N) at a case-specific TOV.

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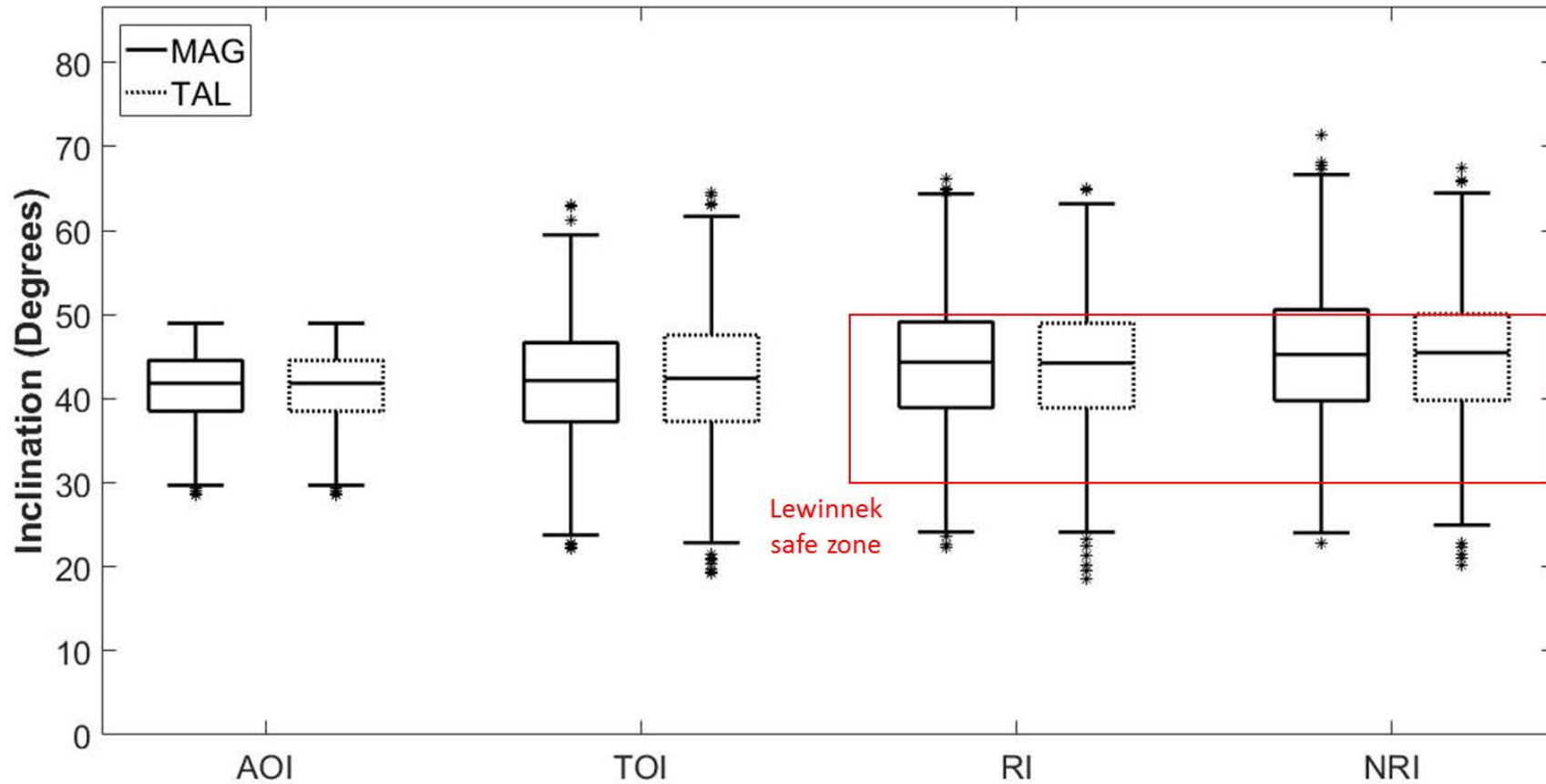
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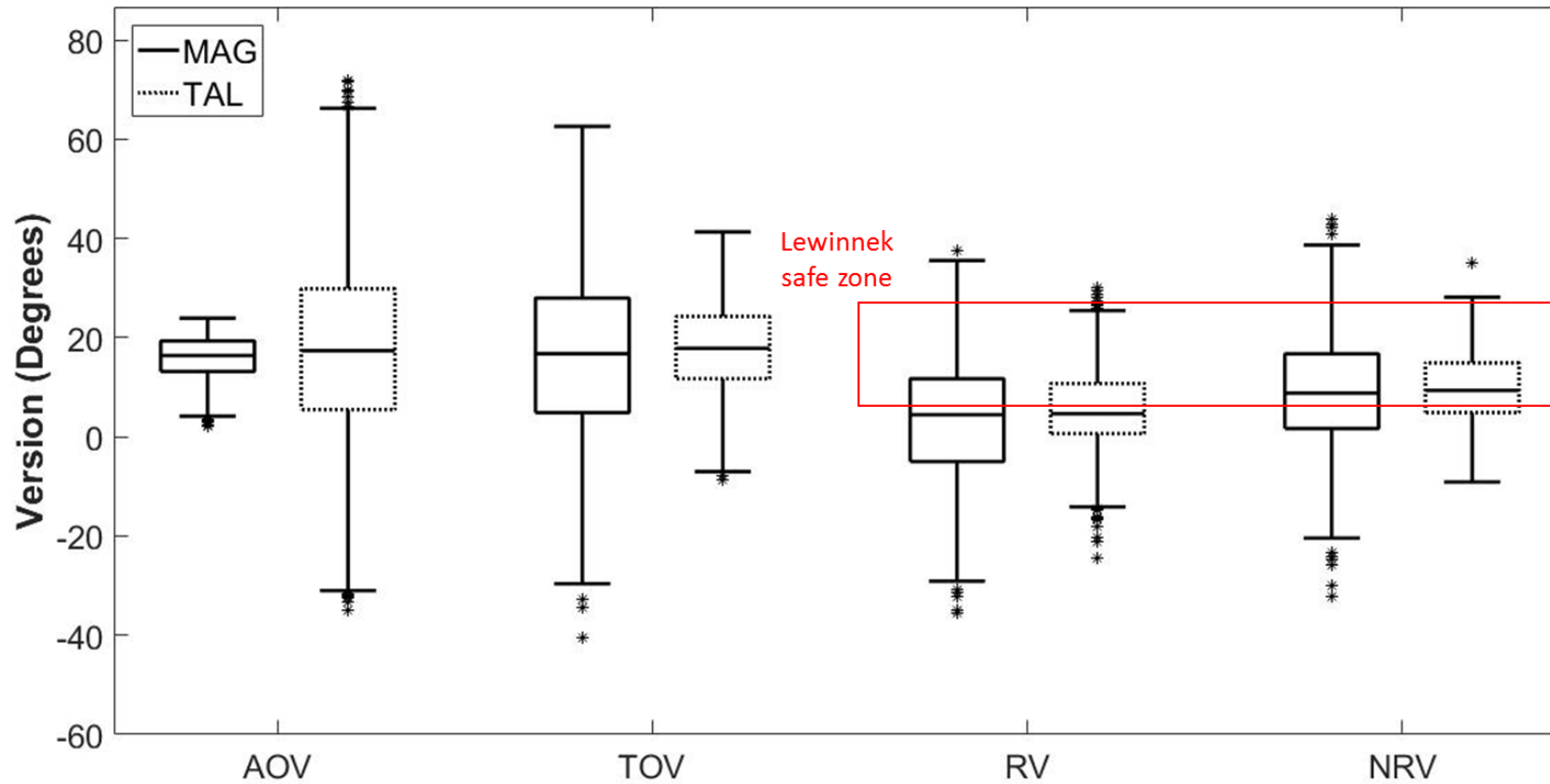
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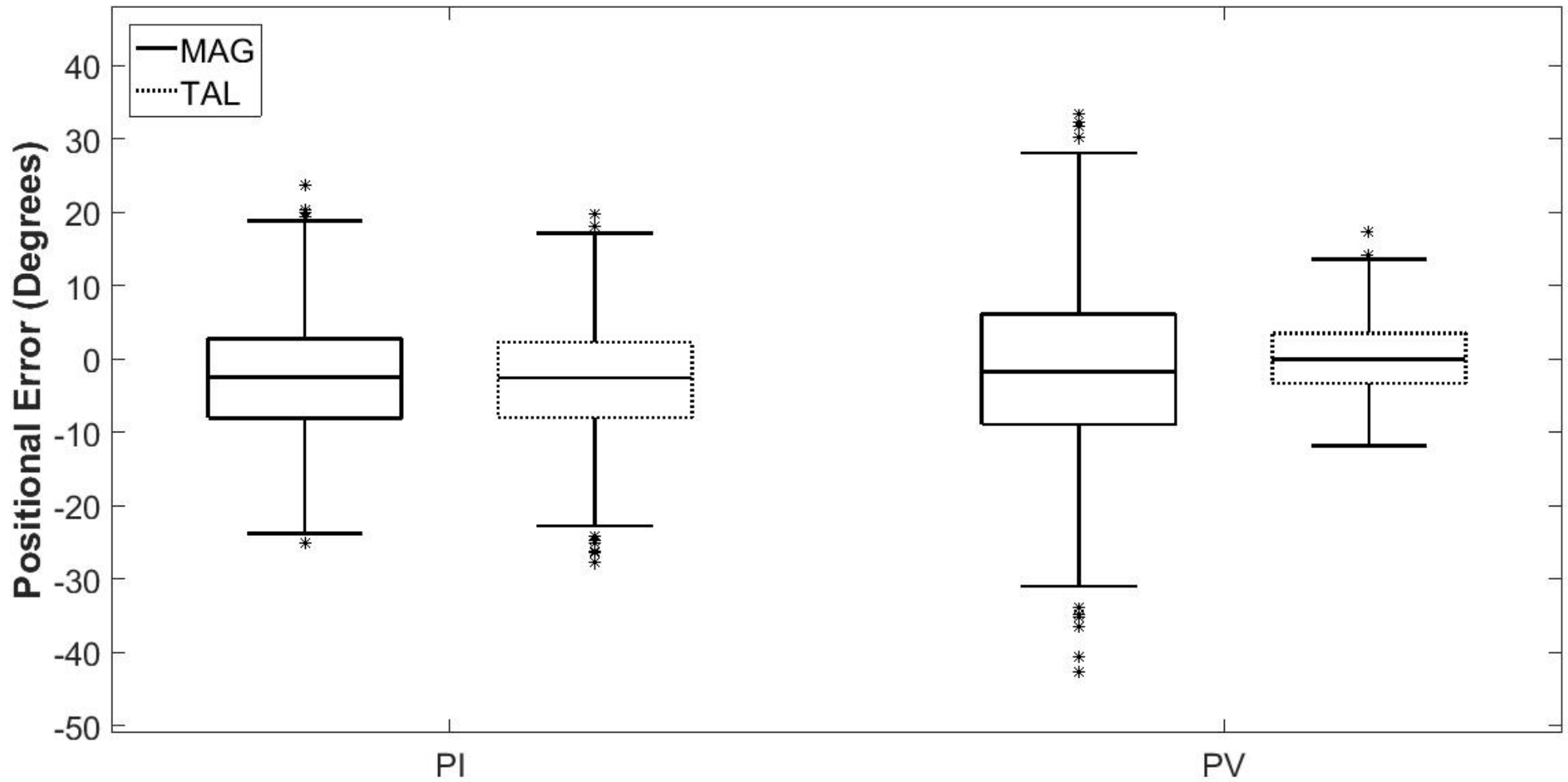
504 Figure 6: Measures of Inclination. No statistical differences were observed between approaches ($p = 0.243$). Both methods exhibit similar control
 505 over TOI. Operative pelvic orientation doubles the range in inclination that an orthopaedic surgeon would expect to see post-operatively. Outliers
 506 (denoted by *) are defined as those points above $Q3 + 1.5(Q3 - Q1)$ or below $Q1 - 1.5(Q3 - Q1)$, where $Q1$ and $Q3$ are the first and third quartiles,
 507 respectively.

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510 Figure 7: Measures of version. Statistical differences were observed between approaches ($p < 0.01$). TAL method results in better control of TOV
511 when compared to MAG. Outliers (denoted by *) are defined as those points above $Q3 + 1.5(Q3 - Q1)$ or below $Q1 - 1.5(Q3 - Q1)$, where Q1 and
512 Q3 are the first and third quartiles, respectively.



513 Figure 8: TAL reduces positional errors for version (PV) but not for inclination (PI). Outliers (denoted by *) are defined as those points above Q3
 514 + 1.5(Q3 - Q1) or below Q1 - 1.5(Q3 - Q1), where Q1 and Q3 are the first and third quartiles, respectively.