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1 **Evaluation of the accuracy of three popular regression equations for hip joint centre estimation using computerized**
2 **tomography measurements for metal-on-metal hip resurfacing arthroplasty patients**

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23 **Abstract**

24 We investigated the accuracy of the regression equations by Bell et al., Davis III et al. and Harrington et al. for hip joint centre (HJC)
25 estimation against the gold standard of Computerized Tomography (CT) measurements of hip joint centre (HJC) for 18 patients with
26 Metal-on-Metal Hip Resurfacing Arthroplasty (MoMHRA). The HJCs were estimated based on the position the left and right Anterior
27 Superior Iliac Spine (ASIS) and the left and right Posterior Superior Iliac Spine (PSIS) identified from a CT scan. Of the three tested
28 regression equations, only those of Harrington et al. produced results that were not significantly different from the patient's 'true'
29 HJCs as measured from the CT scan in all three directions when analysing left and right hips together for both resurfaced and native
30 hips. When native and resurfaced hips were pooled and analysed for left and right, separately, the Harrington et al. regression
31 equations showed significantly different results in the ML direction. Similar estimation errors were observed for native and replaced
32 hips. Since none of the methods tested performed particularly well, we suggest using medical imaging if accurate estimates of HJCs
33 are required.

36 **Introduction**

37 Motion capture is frequently used to assess the functional abilities of patients in clinical practices worldwide. For this, a model of the
38 patient is used to estimate kinematics and kinetics based on surface marker trajectories and ground reaction forces ^[1]. In this process,
39 the hip is frequently modeled as a spherical joint with its joint center (HJC) estimated using regression equations ^[2-4]. However,
40 estimation inaccuracies of the HJCs have been shown to influence the resulting kinematics and kinetics ^[5, 6].

41 Although conventional regression equations ^[2, 3] were derived from the anthropometry of able-bodied adults, they are
42 frequently applied to patients with musculoskeletal pathology. This raises the concern that the HJC estimation may be inaccurate for
43 the patient group they are applied to, potentially leading to inaccurate estimations of the functional abilities of these patients. Recently,
44 however, Harrington et al. ^[4] found no significant differences in the accuracy between adults, children and children with cerebral
45 palsy using the regression equations of Bell et al. ^[2], those recommended by Ortho Trek (Motion Analysis Corp., USA) and the
46 equations of Davis et al. ^[3].

47 Metal-on-Metal Hip Resurfacing Arthroplasty (MoMHRA) is an alternative treatment option for young and active patients
48 with osteoarthritis of the hip ^[7]. In addition to the differences in pelvis and femur geometry, arising from the resurfacing surgery,
49 morphological features have been shown to be associated with the development of hip pathology ^[8]. This implies that geometric
50 differences may exist between the normal and the pathological hip joint. Thus, the accuracy of applying the HJC regression equations
51 to the MoMHRA patient group remains unknown and assessment of this accuracy of three popular regression equations for this patient
52 group was the purpose of this study. Computerized Tomography (CT) was used as a gold standard for estimation of the patients 'true'
53 HJCs.

55 **Methods**

56 Eighteen MoMHRA patients (10 females, 8 males, age 58±10 years, height 1.70±0.09 m, mass 73±13 kg) participated in this IRB
57 approved study. Sixteen subjects had MoMHRA implanted unilaterally whereas two had a total hip replacement (THR) on the contra-
58 lateral limb. Eleven subjects had a Birmingham Hip Resurfacing (Smith and Nephew, UK) and seven subjects had a Conserve Plus
59 (Wright Medical Technology, USA) implanted.

60 For each patient, a CT scan was taken in the transverse plane using a high-resolution 64-slice CT scanner (Somatom,
61 Siemens Medical Solutions, Inc., USA) with the patient in a supine position using a metal artifact reduction sequence.

62 From the CT scans, the Anterior Superior Iliac Spine (ASIS), Posterior Superior Iliac Spine (PSIS) bony landmarks and the
63 ‘true’ HJCs were identified. The ‘true’ HJC of the implanted and the native hip were computed using two different methods. For the
64 native hip, the ‘true’ HJC was found by segmenting the femoral head using Mimics v. 14.1 (Materialise, Belgium) and taking the
65 centre of a sphere fitted to this 3D geometry using Geomagic Studio v. 11.0 (Geomagic, USA) (Figure 1(A)). Sphere-fitting was
66 impossible for the implanted hip due to metal artifacts, therefore the ‘true’ HJC for MoMHRA hips was estimated using six points on
67 the edge of the acetabular component and defining a plane on the open face of the component. The average centre of circles fitted
68 through combinations of three of the six points was found. The normal to the plane at this center point was determined and the HJC
69 estimated as a point projected along the normal based on each patient’s component radius and coverage angle (Figure 1(C)):

$$d_p = \frac{r_c}{\cos\left(\frac{\theta}{2}\right)} \quad (1)$$

71 d_p is the distance projected along the surface normal, r_c is the component radius and θ is the coverage angle.

72 The acetabular component in MoMHRA is not a complete hemisphere. The coverage angle for the Conserve Plus hip
73 resurfacing was assumed to be 170°. For Birmingham Hip resurfacing, the coverage angle varied with component size ^[9].

74 Subsequently, the HJCs were estimated based on the identified bony landmarks using the regression equations of Bell et al.
75 ^[2], Davis et al. ^[3] and Harrington et al. ^[4]. All HJCs were computed in a common reference frame defined by the identified bony
76 landmarks; the origin was located midway between the ASIS bony landmarks with the Medial-Lateral (ML) axis from the left to the
77 right ASIS bony landmarks. The Anterior-Posterior (AP) axis was constructed as the line orthogonal to the ML-axis from the midpoint
78 of the two PSIS bony landmarks. The Superior-Inferior (SI) axis was constructed as the cross product between the AP- and ML-axis
79 (Figure 1(B)).

80 Mann-Whitney U statistical tests were performed on the vector difference and distance between the estimated HJC and the
81 ‘true’ HJC. Finally, the above analysis was repeated for native and replaced hips, separately with the left and right hips pooled to
82 obtain larger populations. Symmetry between left and right were assumed and the ML coordinates for the left hips were multiplied by
83 minus one before being pooled with the right hips.

85 Results and Discussion

86 When comparing the estimations for the replaced and native hips pooled together, the regression equations of Bell et al. ^[2] and Davis
87 et al. ^[3] showed significant differences for two out of the four tested variables, bilaterally (Figure 2). The regression equations of
88 Harrington et al. ^[4] showed no significant differences for the right hips, but a significantly different result in the ML direction for the
89 left hips.

90 The analysis of native and resurfaced hips, separately, showed that the regression equation of Bell et al. ^[2] and Davis et al. ^[3]
91 had significantly different results for at least two of the four measures (Figure 3). The ones of Harrington et al. ^[4] showed no
92 significant differences in any of the four measures. However, the regression equations of Harrington et al. ^[4] showed estimation errors
93 of up to 13.9 mm, 9.1 mm and 12.5 mm for the native hips and 12.4 mm, 13.0 mm and 15.0 mm for resurfaced hips in the AP, SI and
94 ML directions, respectively.

95 Stagni et al. ^[6] studied how HJC mis-locations affect the resulting hip and knee angles and moments for five able-bodied
96 subjects during gait. They concluded that the results are most sensitive to mis-locations in the anterior, lateral and posterior directions.
97 Based on their results and Figure 3, the use of the regression equations of Harrington et al. ^[4] may be recommended among the three
98 tested methods. The regression equations of Bell et al. ^[2] produced significant errors in the AP direction as well as errors in the lateral
99 direction of up to 16.4 mm. The ones of Davis et al. ^[3] produced errors up to 21.0 mm in the posterior direction, which may have
100 significant impacts on the predicted hip moments should this regression equation be used in the model.

101 In clinical practice, skin markers are used as indicators of the underlying bony landmarks and additional errors arising from
102 skin marker misplacements must be expected to be added to the error estimates presented here. This could potentially both make the
103 estimates better or worse, depending on the direction of the misplacements.

104 In conclusion, resurfaced and native hips showed similar errors and the regression equations by Harrington et al. ^[4] generally
105 predicted the patients 'true' HJCs best. However, we suggest using medical image measurements of HJCs if accurate estimates are
106 required.

108

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111

112 **Conflict of interest statement**

113 There are no conflicts of interest for any of the involved authors

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116

117 **Figure labels**

118

119 **Figure 1:** (A) The HJC for the native hips were determined by segmenting the patient’s femur and fitting a sphere to the femoral head.
120 (B) Top view of a scanned pelvis including the defined reference frame in blue. The transparent red spheres show the identified bony
121 landmarks. (C) The method employed to estimate the HJC for the resurfaced hip.

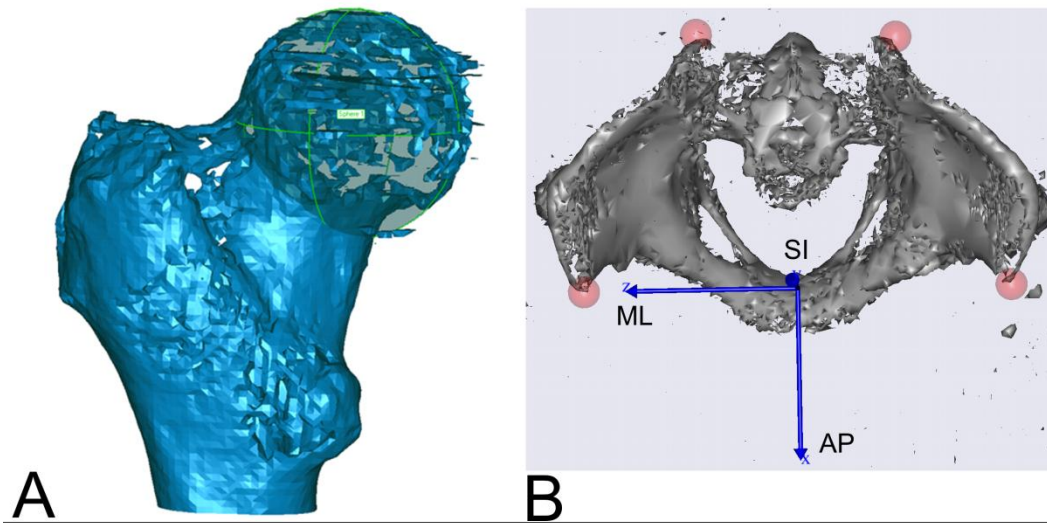
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123 **Figure 2:** Box and whisker plot of the results for the HJCs estimations; distance in each plane and the linear distance relatively to the
124 ‘true’ HJC from CT are depicted separately. Outliers are denoted with an asterisk. Significant differences between the regression
125 equation and the ‘true’ HJC are indicated with a black square. Significance is reported for $p < 0.05$. (A) Shows the left HJCs and (B)
126 the right HJCs.

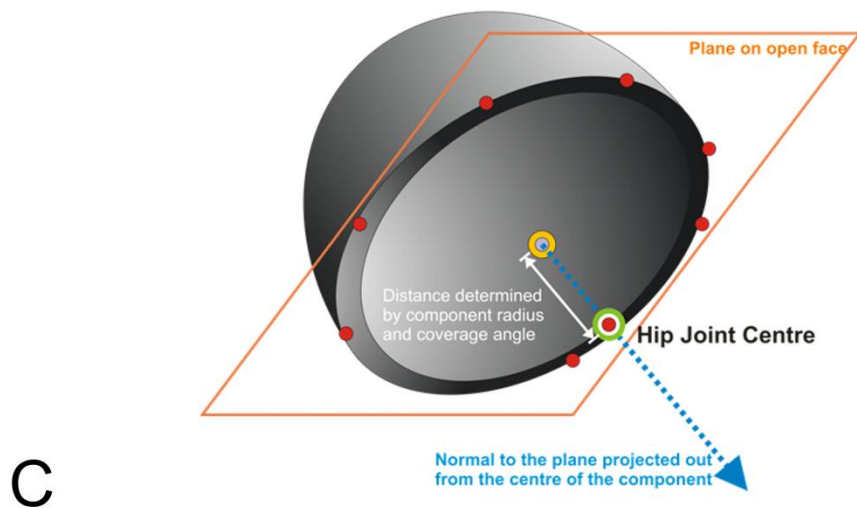
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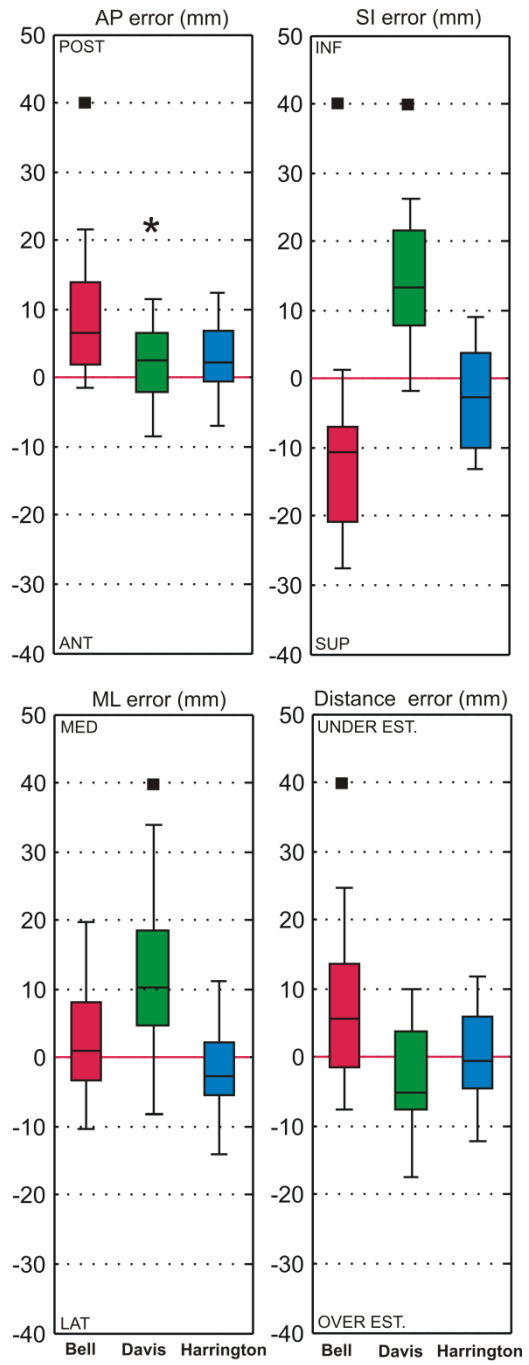
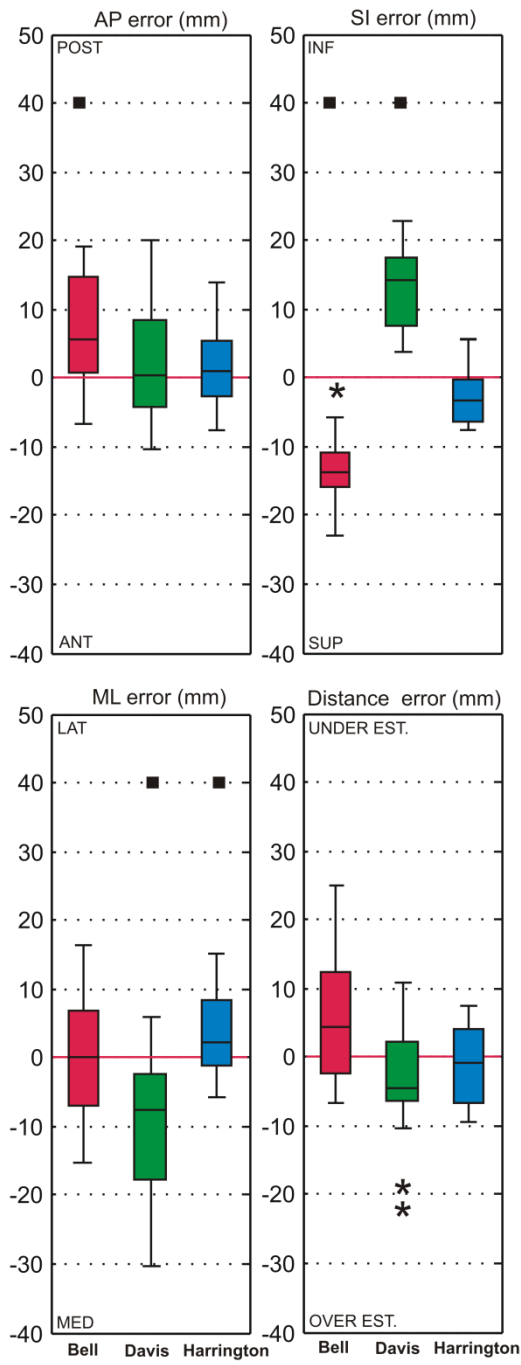
128 **Figure 3:** Box and whisker plot of the HJC prediction errors for the native and replaced hips, separately; AP, SI, ML and the linear
129 distance relative to the ‘true’ HJC from CT are depicted, separately. Outliers are denoted with an asterisk. Significant difference
130 between the regression equation and the ‘true’ HJC is indicated with a black square. N: Native. R: Replaced. Significance is reported
131 for $p < 0.05$.

132



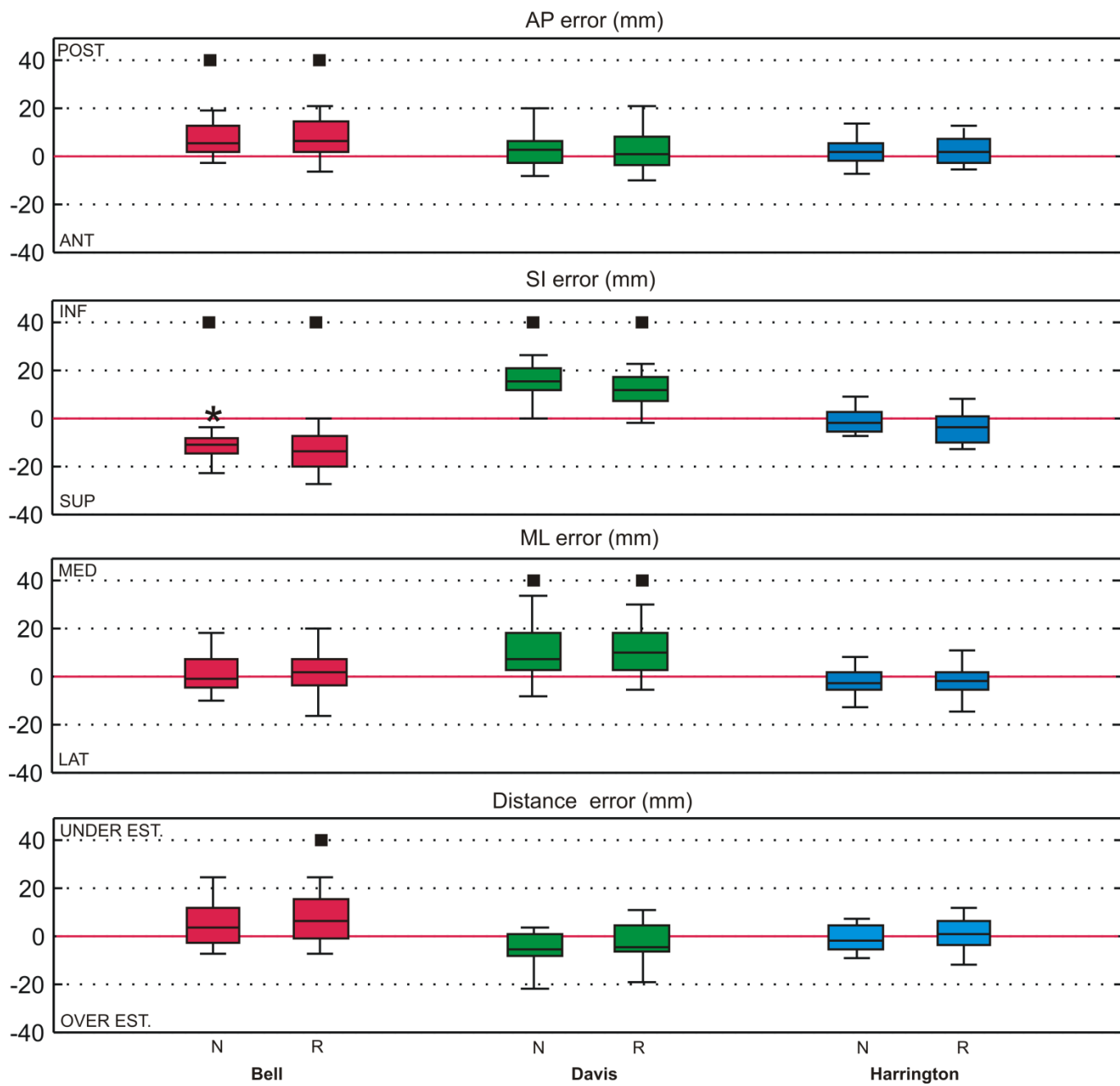
● Points chosen on edge of component (from CT scan)





A Left HJCs

B Right HJCs



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