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Effect of cup medialization on primary stability of press-fit acetabular cups

Federico Morosato, Ph.D[1], Luca Cristofolini, Ph.D[1], Francesco Castagnini, MD[2], Francesco Traina, MD, PhD [2,3]

[1] Department of Industrial Engineering, School of Engineering and Architecture, Alma Mater Studiorum - Università di Bologna, Bologna, Italy

[2] Chirurgia Protesica, IRCCS Rizzoli Orthopaedic Institute, Bologna, Italy

[3] Department of Biomedical and Neuromotor Sciences - Università di Bologna, Italy

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Corresponding author:
Luca Cristofolini
Department of Industrial Engineering
University of Bologna
Via Umberto Terracini 24-28
40131 Bologna, Italy
e-mail: luca.cristofolini@unibo.it

ABSTRACT

Background: Appropriate restoration of the native centre of rotation is of paramount importance in total hip arthroplasty. Reconstruction of the centre of rotation depends on reaming technique: conventional approaches require more cup medialization than anatomical preparations. To date, the influence of cup medialization on socket stability in cementless implants is still unknown.

Methods: Ten cadaveric hemipelvises were sequentially reamed using anatomical technique (only subchondral bone removal with restoration of the native centre of rotation) and conventional preparation (reaming to the lamina and medializing the cup). A biomechanical test was performed on the reconstructions. Implant motions were measured with digital image correlation while a cyclic load of increasing magnitude was applied.

Findings: No significant difference was measured between the two implantation techniques in terms of permanent cup migrations. The only significant difference was found for the cup inducible rotations, where the conventional technique was associated with larger rotations.

Interpretation: Conventional reaming and cup medialization do not improve initial cup stability. Beyond the recently questioned concerns about medialization and hip biomechanics, this is another issue to bear in mind when reaming the acetabulum.

Keywords:

Acetabular reaming depth; Hip Centre of rotation; Cup medialization; implant primary stability; permanent migrations; inducible micromotions.

INTRODUCTION

Restoration of centre of rotation (CoR) is of paramount importance in total hip arthroplasty (THA)[1,2,3]. Anatomical reconstruction of the CoR improves hip biomechanics and function, reduces wear and impingement[1,3]. CoR restoration is strongly dependent on the reaming technique, as well as on the socket design[1,2]. The conventional technique relies un uncemented cups and aims aims to the acetabular floor (*lamina quadrilatera*), medializing the CoR[4]. On the other side, the anatomical method requires only peripheral reaming, limited to the acetabular rim, thus respecting the anatomical medial-lateral position of the CoR[4].

The claimed advantage of conventional technique is mainly due to a two-dimensional concept of the lever arms: CoR medialization improves the abductor muscle moment arm [5,6]. However, a recent CT-based finite element analysis highlighted that CoR medialization improves abductor biomechanics only in some cases (low femoral ante-torsion) and at some costs (reduction of flexion-extension moment arms)[7]. Moreover, cup medialization may sacrifice a large amount of bone stock, may significantly reduce the acetabular offset (with clinical implications) and may change the joint reaction forces, the proprioception and the muscle functionality[1,3,4,7]. On the contrary, anatomical reaming reduces cup medialization to a minimum, preserving the medial-lateral position of the native CoR and the bone stock. However, it may result in socket under-coverage or overhanging, potentially causing psoas impingement[1,3,4]. To date, there is no evidence that a reaming technique is clearly superior over the other, leaving the choice to surgeon's discretion[4,7]. However, the influence of reaming technique (and thus, cup medialization) on stability of cementless press-fit sockets has not been adequately investigated. In particular, it is not ascertained if deeper cup positioning may reduce the initial inducible (or elastic) implant micromotions that prevent osseointegration and may lead to cup loosening[8,9,10].

A cadaveric biomechanical study was designed to compare the effects of two different reaming techniques (conventional and anatomical), and consequently, two different cup medializations, on primary stability of press-fit acetabular cups in the same acetabulum. We hypothesized that deeper implantation (conventional technique, more medialization) provided better implant stability. In particular, stability was assessed in terms of three-dimensional permanent migrations and inducible micromotions between the cup and the host bone.

MATERIALS AND METHODS

To assess the effect of implantation depth (medialization) on primary stability of press-fit acetabular cups, ten cadaveric hemipelvises were used. Specimens were implanted in two different fashions. First, the cups were implanted after a peripheral reaming technique (anatomical implantation). After the biomechanical test, the specimens were reamed until reaching the *lamina quadrilatera* and implanted with the same cup (conventional implantation). Digital image correlation (DIC) was used to measure the relative 3D implant/bone motion[11].

Preparation of the specimens

This Study was authorized by the Bioethics Committee of the University of Bologna (Prot. 179610, 7 December 2018). Ten paired fresh-frozen hemipelvises were obtained through ethically-approved donation programs (Table 1). No information about donor's laterality was available. The bones were wrapped in cloths soaked with physiological saline solution and stored at -30°C when not in use, and were thawed at room temperature prior to testing. The entire preparation and testing procedure lasted approximately 3 hours for each specimen. The soft tissues around the acetabulum were removed. Each hemipelvis was aligned in a reproducible reference frame and potted in correspondence of the sacro-iliac joint with bone cement (Fig. 1)[12]. To avoid excessive bending during the biomechanical test, a constraint was added in the pubic symphysis (Fig. 2).

Spherical plugs with controlled dimensions were used to measure the cup size required for each acetabulum, and to estimate the position of the native anatomical CoR (Fig. 1). To avoid the effects on anatomical variability, the same cup size was used for both implantations in the same hemipelvis (Table 1). An experienced hip surgeon (FT) performed reaming and implantation so as to correctly prepare the hemipelvises according to the two implantation techniques. In both cases, the cup was implanted so as to obtain 45° inclination and 20° anteversion, according to previous methodological studies[11,12].

- Anatomical implantations (less deep cup position): peripheral reaming was performed aiming to restore the native CoR as close as possible, with a minimal medialization and circumferential, complete cup coverage. Commercial primary cups (Plasma fit® Plus, Aesculap AG, Tuttlingen, Germany) were implanted. To ensure that the cups were within ±2mm from the native CoR, the position of the cup centre after implantation was measured (Fig. 1) (Table 1). Ceramic liners (Biolox® Delta, Ceramtec, Plochingen, Germany) were inserted. After the biomechanical test (see details below), the cups were extracted.

- Conventional implantation (deeper cup position): each acetabulum was progressively medialized by further reaming to the *lamina quadrilatera* (using the same reamer size as in anatomical technique), aiming to maximize the difference from the CoR achieved with anatomical implantation. The position of the CoR of such conventional implantation was measured and compared with the position of the CoR previously achieved (Fig. 1). A difference of position smaller than 3mm required the specimen to be reamed deeper (if possible) and re-implanted. In one case this was not possible, and the specimen was excluded. Two extremely osteoporotic specimens were fractured in the posterior column during implantation and were not tested. Therefore, seven specimens were finally available with both implantation techniques (Table 1). The ceramic liners were inserted, and the same biomechanical test was repeated.

Biomechanical testing

In order to reproduce a critical loading configuration, standing up from seated was selected among the typical post-operative patient activities [13]. Such motor task generates the highest load peak in the acetabulum compared with other post-op activities[14], and it results in a migration direction of the cup consistent with that observed clinically[15]. In particular, the direction of the peak force measured *in vivo* during standing up from seated was identified from the open dataset by Orthoload Club[14]. It is important to stress that the dataset of *in vivo* forces was used to identify the relevant force direction, whereas the magnitude of the applied force increased during the test in a standardized way, so as to avoid the risk of specimen damage, while enabling a comparison of the two implantation techniques. The specimens were aligned in the testing machine so as to apply the force in the selected direction (Fig. 2). A system of low-friction linear bearings was used to avoid transmission of any other undesired force components. A uni-axial servo-hydraulic testing machine (Mod. 8800, Instron, UK) was used to apply packages of cyclic load with increasing magnitude similar to Morosato *et al.*[15]. To account for the donor's anatomy, loading was scaled according to the donors' body weight (BW). Each package consisted of 50 load cycles. The first load package reached a peak force of 1BW, the following packages were always 10% larger than the previous one (Fig. 2).

As each specimen had to be tested twice (with the two implantation techniques), it was crucial to prevent a sequence effect due to damage or conditioning. Therefore, a coarse stop criterion was implemented during the first test session (anatomical implantation) in real time throughout the test: the test was continued (with load packages of increasing magnitude) until the measured cup permanent migration exceeded 0.5 mm. In addition, if the strains measured with DIC (see below) exceeded 2000 microstrains (i.e. similar to the physiological deformations experienced by bone[16]) the test was stopped. To allow paired comparisons between the two implant conditions, each specimen was tested after conventional implantation up to the same load reached in the previous testing with anatomical implantation.

Measurement of implant motion

As the digital image correlation (DIC) software requires the surface to have a high-contrast speckle pattern, a black-on-white pattern was painted on the periprosthetic bone and one the rim of the cup insert before the biomechanical tests[11]. A commercial DIC system (Q400, Dantec-Dynamics, Denmark) was used to measure the motions of the implant and of the bone throughout the test, following a validated procedure[11]. The system also allowed to measure full-field strains during the test. Two cameras (5 MegaPixels, 8-bit) with high-quality metrology-standard 17-mm lenses (Xenoplan, Schneider-Kreuznach, Bad Kreuznach, Germany) were used to obtain 3D measurements. The cameras were positioned so as to frame the implant, the superior aspect of the acetabulum, part of the iliac wing and of the posterior column (Fig. 2).

In order to compute the three components of translation and rotation of the implant, the DIC-measured displacements were post-processed through a dedicated script in Matlab (2017 Edition, MathWorks, Natick, MA)[11]. In particular the permanent migration (i.e. the migration accumulated cycle after cycle), and the inducible micromotion (i.e. the recoverable motion between load peak and valley) were analysed.

Statistical analysis

The sample size was defined based on a previous similar study that allowed predicting measurement uncertainty [11,15]. A sample of N = 5 was estimated for detecting 150 micrometers motion (the threshold for implant loosening[8,9,10]), with alfa = 0.05 and beta = 0.2. This relatively small sample size is due to the high measurement precision, and of the use of the specimens in a paired fashion.

To assess if the effect of the two implantation techniques on implant motions was statistically different, a Wilcoxon signed-rank test was performed using Matlab. The level of significance was $p = 0.05$ for all analysis. The following results were analysed as paired data (the same load peak was reached for the two implantation techniques in each specimen):

- The cup migration after the application of the last load package in the anatomical vs the conventional implantation.
- The median of the inducible micromotions during the last load package in the anatomical vs the conventional implantation.

RESULTS

The permanent translations at the end of the biomechanical test ranged 0.064 - 0.354 millimetres for the anatomical implantations and 0.065 - 0.210 millimetres for the conventional ones. The inducible micromotions never exceeded 0.130 millimetres for both types of implantation. The resultant permanent translation was slightly larger for the conventional implantation than for the anatomical one (not statistically significant, Fig. 3). However, looking at the single components, the permanent translations were slightly larger for the anatomical implantation (again, with no statistical significance). A similar trend was found for the inducible translations, with no statistically significant difference (Fig. 3).

The permanent rotations at the end of the biomechanical test ranged 0.001° - 0.59° for the anatomical implantations and 0.006° - 0.30° for the conventional ones. The inducible rotations never exceeded 0.20° millimetres for both types of implantation. No significant difference was detected between the permanent rotations of the two implantation techniques (Fig. 4). The only statistically significant differences were detected for the inducible rotations around the antero-posterior and around the medio-lateral axis (Fig. 4).

A detailed analysis of the individual specimens highlighted that there was no correlation nor visible trend between the difference between the two implantation depths (Table 1) and the implant motions (both inducible and permanent).

DISCUSSION

Cup medialization, and reaming technique, has implications for hip biomechanics (muscle lever arms, offset) and bone stock: some of these effects are still under question[1,4,7]. Another issue about cup medialization is still unanswered: if cup medialization may improve the initial cup stability of press-fit sockets and, thus, may promote a better bony ingrowth through minimization of micromotions.

Thus, an *in vitro* biomechanical study was performed on human hemipelvises. Press-fit acetabular cups were implanted, first aiming to restore the native CoR (anatomical implantation), then reaming to the lamina (conventional technique), maximizing the distance between the position of the CoR achieved with the two techniques. Thus, cup medialization was progressively increased (median value: 3.4 ± 0.4 mm). The hypothesis was: cup medialization, and thus conventional reaming technique, improved primary cup stability. However, the biomechanical results showed that anatomical and conventional implantations produced comparable implant motions. The permanent translations and rotations were similar for the two techniques, with no statistically significant difference. Only inducible rotations around the antero-posterior and the medio-lateral axes were significantly different. However, such rotations were so small in all cases (less than 0.04°, close to the intrinsic error of the measurement protocol[11]).

A few biomechanical studies focusing on the relationship between cup medialization and implant stability can be found in the literature. To the Author's best knowledge, only one study assessed the effect of reaming depth, bone defects and under-reaming in Sawbones foam block and bovine spongy bone specimens[17]. Adler *et al*. concluded that proper bone preparation (hemispherical cavity with no focal defects) and cup medialization (5 mm) improved cup stability. They proposed that cup medialization may have overcome dense subchondral bone and polar gaps, providing more stability[17]. O'Rourke *et al*. partially supported these suggestions, highlighting a non-significant correlation between polar gaps and intact acetabular depth (that is, minimal medialization) in a cohort of patient-specific finite element models[18].

These findings were not supported by the present study: even if the surgeon aimed at medializing the CoR as much as possible, cup medialization did not significantly improve cup stability. It is likely that the 3 mm medialization provided by conventional reaming technique in the study was too modest to provide a significant difference in cup stability. As a matter of fact, Adler *et al*. implanted the cups at three medial-lateral configurations, reaming 5 mm deeper every time[17]. While in some laboratory settings, a 5 mm medialization may be possible, such an aggressive reaming seems not suitable for many pelvic morphologies in *in vivo* studies (66% of the acetabula, mainly female ones)[4]. In a CT-based study, Bonnin *et al*. implanted press-fit cups on 100 hips using conventional and anatomical techniques, achieving a mean cup medialization of 3.2 ± 1.9mm, similar to our study[4]. Moreover, the medial-lateral position of the cup plays a complex role in the whole hip biomechanics, impacting on offset and range of motion[19]. Aggressive medialization may definitively violate the acetabular offset and, in some cases, increasing femoral offset is not sufficient to compensate for the global loss of lateralization[3]. As a consequence, hip abductors lever arm may be significantly reduced, with a possible clinical impact[4,7,20]. Moreover, recent literature highlighted that cup medialization and loss of offset were associated to increased wear of polyethylene liners and increased stresses at the bone-implant interface in press-fit sockets, overturning the classic perspective "more cup medialization-less loosening" (based on cemented cups and very old implants)[4,21,22,23]. Conversely, anatomical reaming provides accurate CoR reconstruction, adequate offset restoration and, as the present study highlighted, sufficient cup stability[1,3,4]. It also preserves bone stock, which is of paramount importance, considering that THAs are more and more common in younger patients and the revision rate is steadily increasing[4,24].

The two consecutive reaming techniques performed on the same acetabulum are a limitation of this study. The anatomical reaming and the subsequent biomechanical tests may have partially influenced the shape of the second acetabular cavity and the grip of the second cup implantation. Furthermore, the conventional reaming was performed using an "anatomical technique": the last reamer used for peripheral acetabular preparation was aimed to the *lamina* (and, thus, without progressively increasing the reamer sizes from the beginning of the preparation). In this way, reaming is concentric with a medial-lateral vector (superior-inferior and anterior-posterior displacements do not take place) and cup medialization is the sole positioning variable. Moreover, the use of the same hemipelvis for both types of implantation reduced the influences of the anatomical features of the native acetabulum (e.g., dysplasia or bone quality) on cup stability, allowing a direct comparison of the two treatments without confounding anatomical factors. A single loading configuration was applied in our biomechanical tests, reducing the complexity of the forces acting in the acetabulum to a single resultant force. This simplification was demonstrated to be suitable to generate *in vitro* implant motions consistent with the clinical observations[15]. Our study had a limited sample size (N=7), but this was sufficient to provide adequate statistical, as the same specimen was used in testing of anatomical and conventional implantation. A similar sample size is often used in *in vitro* implant stability tests[25,26]. The need to prevent bone damage (to allow testing each specimen in two implant conditions) forced us to limit the magnitude of the forces applied during the test. Therefore, absolute implant motions in real patients might be larger than those found in our tests. However, implant motions were analysed in comparative terms, thus allowing to assess differences between anatomical and conventional implantation. Moreover, keeping the force magnitude low allowed to avoid the risk of specimen conditioning due to the two tests being applied to the same specimens. This study did not include any evaluation of the global and femoral offset restoration as this was not the focus of this experiment.

CONCLUSIONS

This study demonstrated that cup medialization did not improve initial stability of press-fit sockets. This finding tends to support a more circumferential reaming instead of the conventional method. In fact, the classical belief that cup medialization provides biomechanical benefits has been recently questioned[7]. Cup medialization may increase wear rate, stresses at the bone-implant interface, loss of bone stock and loss of offset, with significant effects on implant survival, biomechanics and stability[1,2,3,21,22]. Conversely, anatomical reaming closely restores the native CoR and provides sufficient initial cup stability. Long-term studies comparing the two reaming techniques in the same patients (bilateral THAs) may provide additional decisive data about the clinical consequences of these two surgical approaches, in particular aseptic cup loosening, polyethylene wear and implant stability.

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TABLES

Table 1 - List of specimens, including the donors' details, and the size of the implanted cups. The position of cup with respect to the native centre of rotation is reported for the anatomical and conventional implantation (negative values indicate that the cup was inserted deeper than the native CoR). The last column reports the difference between the two implantations.

Donor	Cause of death	Sex	Age (years)	Height (cm)	Body weight (kg)	BMI (kg/m^2)	Side	Cup size (mm)	Cup centre Anatomical implantation (mm)	Cup centre Conventional implantation (mm)	Difference btw anatomical and conventional (mm)
#1	Sepsis	F	83	164	63	23	L	56	2.0	-1.8	3.8
							R	56	1.1	fractured	-
#2	Respiratory paralysis	M	70	175	79	26	L	52	1.3	-2.1	3.4
							R	54	0.9	-2.2	3.1
#3	Unknown	M	74	176	78	25	L	48	0.4	fractured	-
							R	48	-1.6	-5.6	4.0
#4	Coronary thrombosis	M	71	187	92	26	L	60	1.7	-1.8	3.5
							R	62	-0.7	-1.8	1.1**(*)**
#5	Cardiac arrhythmia	M	61	181	96	29	L	56	1.4	-1.6	3.0
							R	54	1.5	-1.6	3.1
	Median	**-**	**71**	**176**	**79**	**26**	**-**	**55**	**1.2**	**-1.8**	**3.4**
	SD	**-**	**7.9**	**8.5**	**13.2**	**2.2**	**-**	**4.5**	**1.1**	**1.4**	**0.4**

Note (*): this specimen could not be tested because the difference between anatomical and conventional implantation was less than 3 mm.

CAPTIONS OF FIGURES

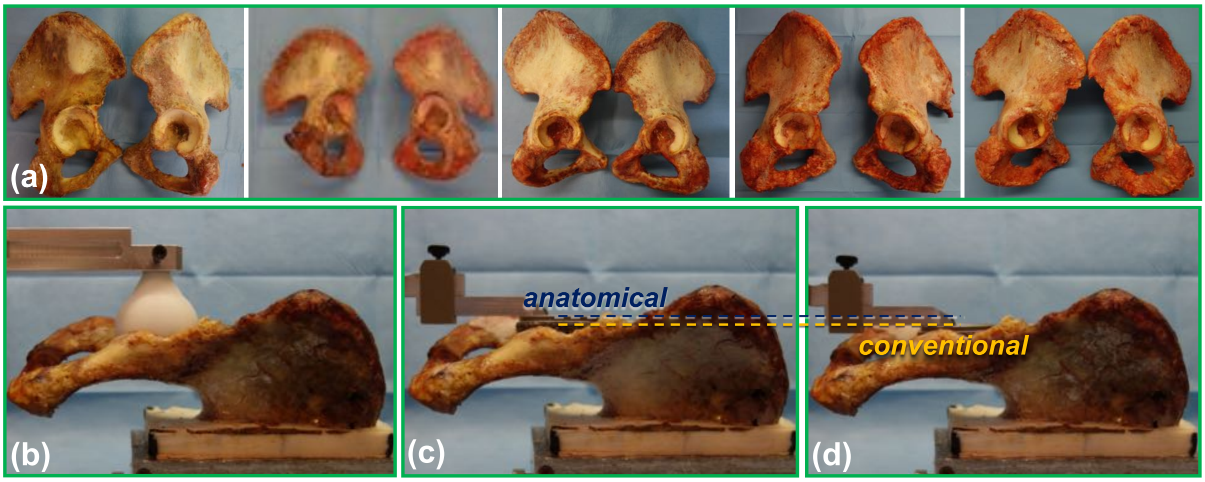

Fig. 1 - Ten paired hemipelvises from five donors were prepared (a). The size of each acetabulum was measured to plan implantation and to record the position of the native anatomical centre of rotation (b). All the specimens were first implanted so as to restore as close as possible the native centre of rotation (anatomical implantation, c) and subjected to biomechanical test. The specimens were then implanted after reaming towards the *lamina quadrilatera* (conventional implantation, d). The specimens in c) and d) were tilted so that the acetabular rim was horizontal.

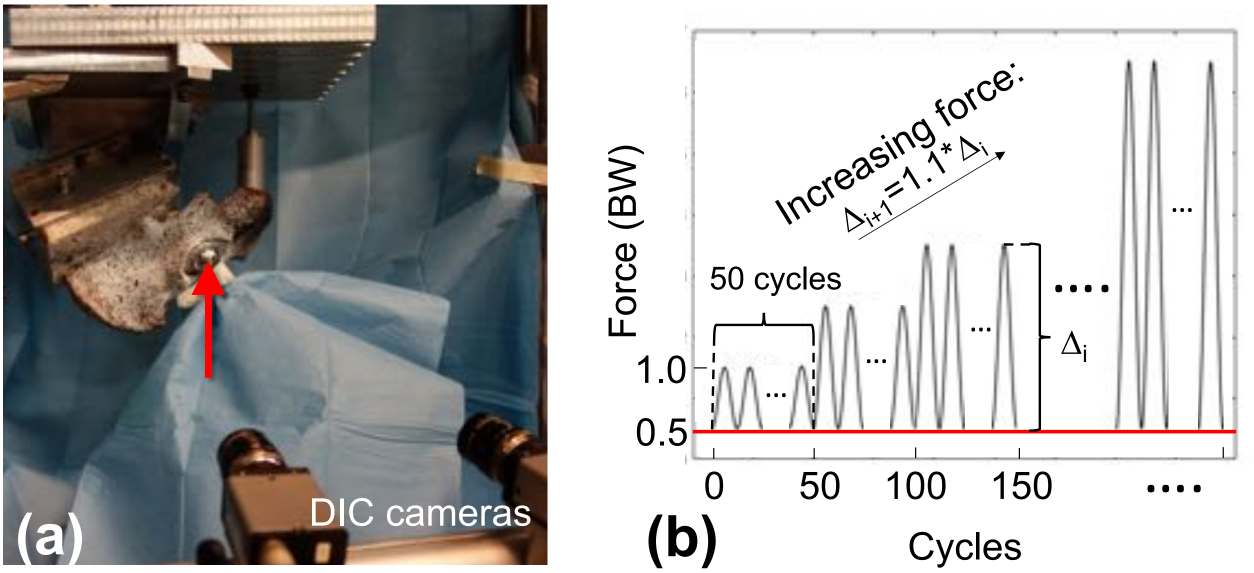

Fig. 2 - The specimen was mounted in the testing frame so as to apply a force (red arrow) in the selected direction (a); the hemipelvis was constrained through the pot on the sacroiliac joint, and through a support at the pubic symphysis; the cameras of the DIC system were placed so as to frame both the cup and the surrounding bone. Load cycles of increasing magnitude were applied in packages of 50 cycles (b); each load package was 10% larger than the previous one; the force was scaled on the patient body weight (BW).

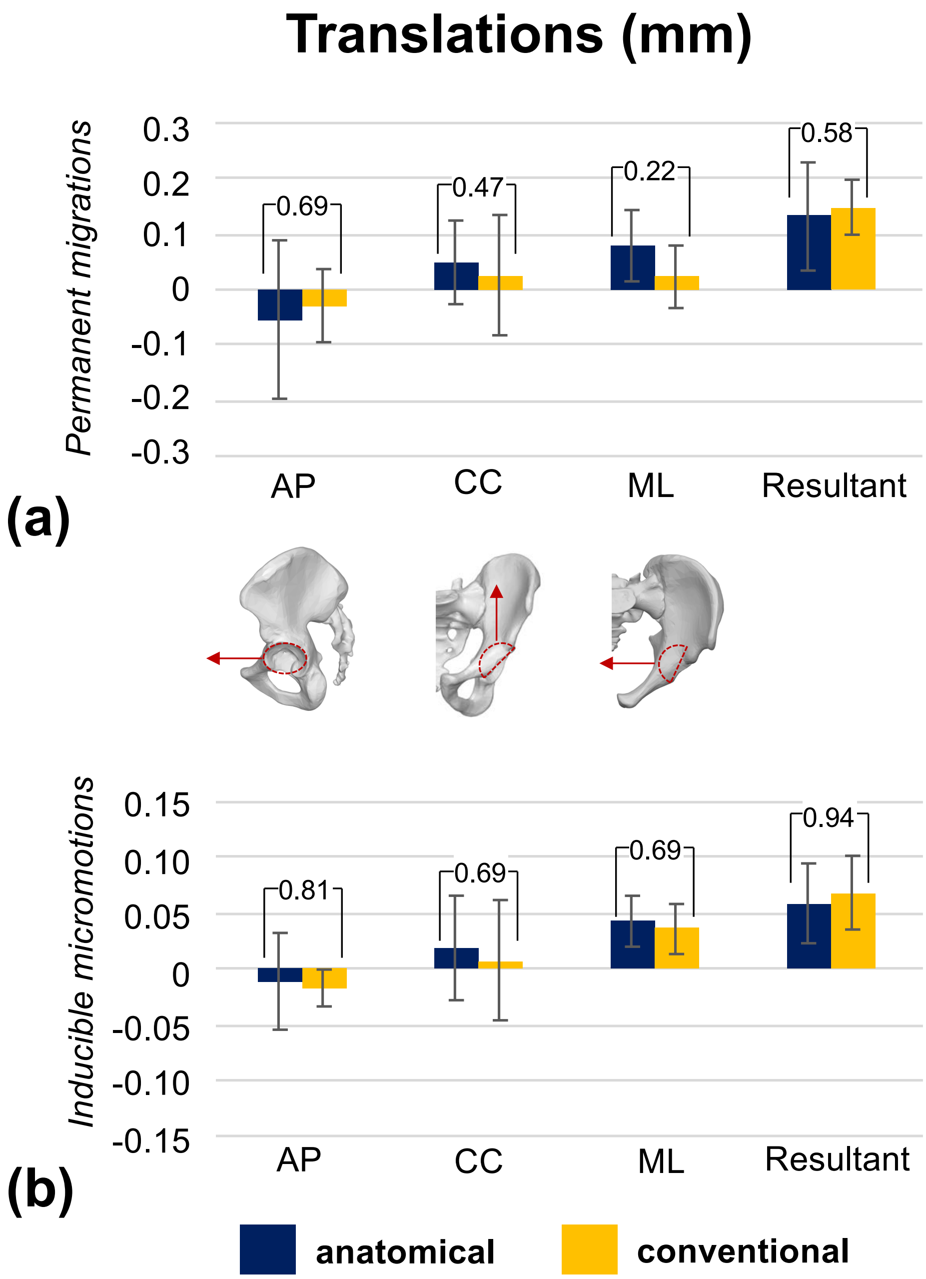

Fig. 3 - Cup translations when the largest load was applied to the anatomical and conventional implantations. The permanent migrations (top) and inducible micromotions (bottom) are presented as components of translation along the antero-posterior (AP), cranio-caudal (CC) and medio-lateral (ML) axis, and as a resultant. The three components of cup translation are sketched together with a hemipelvis from the three views. The bars show the median and standard deviation of seven specimens. The *P*-value from the Wilcoxon signed-rank test is indicated for pairwise comparisons.

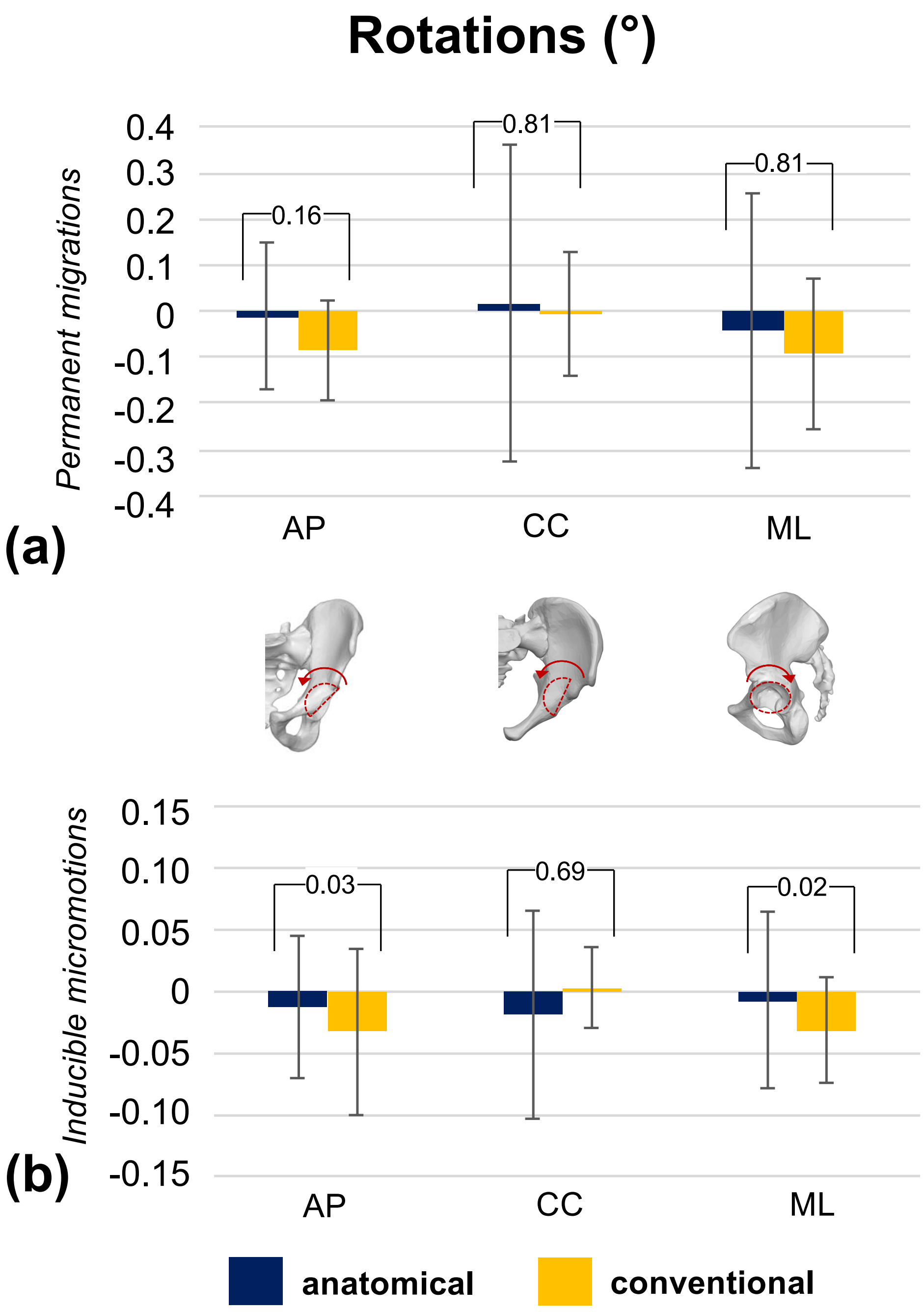

Fig. 4 - Cup rotations when the largest load was applied to the anatomical and conventional implantations. The permanent migrations (top) and inducible micromotions (bottom) are presented as components of rotation about the antero-posterior (AP), cranio-caudal (CC) and medio-lateral (ML) axis. The three components of cup rotation are sketched together with a hemipelvis from the three views. The bars show the median and standard deviation of seven specimens. The *P*-value from the Wilcoxon signed-rank test is indicated for pairwise comparisons.