



## Original article

# What is the best hip center location method to compute HKA angle in computer-assisted orthopedic surgery? In silico and in vitro comparison of four methods



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## ARTICLE INFO

## Article history:

Received 6 July 2018

Accepted 1<sup>st</sup> November 2018

## Keywords:

Hip center

HKA

Computer-assisted orthopedic surgery

## ABSTRACT

**Background:** In computer-assisted orthopedic surgery, the hip center (HC) can be determined by calculating the center of rotation of the femur in relation to the pelvis. Several methods are available: Gamage, Halvorsen, Pivot or Least-Moving Point (LMP). To our knowledge, no studies have compared these four methods. We therefore conducted in silico and in vitro experiments to assess whether their accuracy and precision in locating the HC and calculating the hip-knee-ankle (HKA) angle were equivalent.

**Hypothesis:** The four methods show similar accuracy and precision.

**Patients and methods:** The in silico experiment assessed the independent influence of four parameters (camera noise, acetabular noise, movement amplitude, and number of circumductions) on accuracy. The accuracy and precision of the four methods and the impact on HKA angle calculation were assessed in an in vitro study on six cadaver limbs.

**Results:** In the in silico experiment, all differences according to method were significant ( $p < 0.0002$ ). The Pivot method was the most accurate for acetabular and camera noise, number of circumductions, and movement amplitude. With the LMP, Pivot, Gamage and Halvorsen methods, error was respectively  $23.07 \pm 8.40$  (range 2.10–54.67) mm,  $1.98 \pm 0.81$  (0.15–4.89) mm,  $28.18 \pm 3.42$  (18.57–37.60) mm and  $2.84 \pm 1.46$  (0.11–9.44) mm depending on camera noise,  $1.65 \pm 0.72$  (0.13–4.80) mm,  $0.52 \pm 0.22$  (0.05–1.23) mm,  $3.02 \pm 0.57$  (0.60–4.78) mm and  $0.61 \pm 0.27$  (0.04–1.82) mm depending on movement amplitude,  $0.50 \pm 0.20$  (0.05–1.34) mm,  $0.18 \pm 0.08$  (0.01–0.44) mm,  $0.36 \pm 0.14$  (0.03–0.80) mm and  $0.21 \pm 0.09$  (0.01–0.55) mm depending on number of circumductions, and  $11.30 \pm 5.77$  (0.56–37.87) mm,  $2.78 \pm 1.47$  (0.10–8.77) mm,  $88.08 \pm 8.85$  (60.59–117.79) mm and  $24.33 \pm 9.82$  (1.40–66.17) mm depending on acetabular noise. In the in vitro experiment, differences were non-significant between the Pivot and LMP methods ( $p > 0.98$ ) and between the Gamage and Halvorsen methods ( $p > 0.65$ ). With the LMP, Pivot, Gamage and Halvorsen methods, precision was respectively  $8.2 \pm 4.6$  (3.3–23.6) mm,  $7.3 \pm 3.6$  (3.4–14.1) mm,  $33.6 \pm 19.1$  (4.7–111.4) mm and  $35.0 \pm 25.0$  (4.7–132.5) mm. Accuracy was  $13.5 \pm 8.2$  (3.2–40.7) mm,  $12.3 \pm 6.4$  (3.2–23.6) mm,  $47.0 \pm 33.3$  (6.2–176.6) mm and  $40.3 \pm 27.8$  (6.1–130.3) mm. The LMP and Pivot methods were thus more accurate and more precise than the Gamage and Halvorsen methods. HKA angle error was  $1.1 \pm 0.9^\circ$  (0.1–3.7) and  $0.9 \pm 0.8^\circ$  (0.0–2.5) with the LMP and Pivot methods, and  $3.2 \pm 2.7^\circ$  (0.0–12.7) and  $3.8 \pm 3.5^\circ$  (0.0–13.3) with the Gamage and Halvorsen methods.

**Discussion:** The study highlighted differences between the four methods of HC location in computer-assisted surgery; the pivot method was the most accurate and precise, thus falsifying the study hypothesis.

**Level of evidence:** III, prospective comparative in silico and in vitro study.

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## 1. Introduction

The hip center (HC) is an essential parameter in orthopedic surgery, widely used in many procedures principally involving control or correction of lower limb alignment [1–6]. In computer-assisted (or navigated) orthopedic surgery, there are two approaches to determining the HC:

- anatomic, requiring direct access to the femoral head, of which the HC is considered to be the morphologic center;
- non-invasive functional approaches estimating the HC from the center of rotation of the femur with respect to the pelvis.

Several such functional approaches have been described, and fall into two categories [7]:

- sphere adjustment, considering the HC as the center of a sphere described by the femoral rigid body during circumduction;
- coordinate transformation, based on biomechanical hypotheses to estimate a point corresponding to the HC [3,7–12].

Several sphere adjustment methods have been described [9,13,14], but only the two most precise and accurate are now used: those of Gamage and Lasenby [15] and of Halvorsen et al. [16]. Two coordinate transformation techniques are now mainly used: the Pivot method [12], considering the HC as a fixed point with respect to the femoral rigid body, and the Least-Moving Point (LMP) method [3,10], considering the point which moves least during circumduction to be the HC.

Several studies have assessed these functional approaches, in silico (by mathematical simulation) [3,5,7,9,14,15], and in vitro (on cadaver specimens) [1,6,8,17]. The in silico experiments assessed algorithms in a controlled environment in which several parameters could be simulated to assess their independent impact on results. Some studies assessed just one method [3,7,9,14], while others were comparative [7] although using a small number of parameters. Although necessary, such in silico assessment is insufficient [1,7]. In vitro experiments are closer to real conditions. Several have been performed on cadaver specimens [1,8,17], but assessed only one [17] or two methods [1] and did not analyze the impact of HC location error on the calculation of hip-knee-ankle (HKA) angle. To our knowledge, no studies have really assessed and compared all four methods. We therefore conducted an in silico and in vitro study to determine whether they provided equivalent accuracy and precision in locating the HC. The study hypothesis was that they provide equivalent accuracy and precision.

## 2. Materials and methods

### 2.1. Materials and data

The in silico experiment used a dedicated software application developed for the study, which generated data required for HC calculation by simulating femoral rigid body positions during circumduction around a given HC:  $HC_{reference}$ . The data were calculated from four parameters:

- the movement amplitude;
- the number of circumductions;
- the camera noise, associated with the location system, simulated by a Gaussian noise (with a normal distribution) applied on the positions and orientations of the femoral rigid body;
- and the acetabular noise, which is a single variable representing femoral head non-sphericity or pelvic movement during acquisition, simulated by a Gaussian noise applied to position  $HC_{reference}$ .

The in vitro experiment was performed on six cadaveric lower limbs, pre-checked by an expert to exclude morphologic condylar or malleolar abnormalities, liable to induce imprecision unrelated to HC location in calculating HKA angle.

## 3. Methods

For the in silico experiment, four tests were used to assess independently the influence of four parameters on HC location precision:

- test 1: influence of camera noise;
- test 2: influence of movement amplitude;
- test 3: influence of number of circumductions;
- test 4: influence of acetabular noise.

Table 1 shows parameter values. Each test was run 1000 times. The in vitro experiment used a navigation system comprising:

- an Accutrack 250 optical video camera (Atracsys™; Puidoux, Switzerland) with 0.3 mm root mean square (RMS) precision;
- a computer with Intel® Core™ 2 Duo 2.53 GHz processor with 4 Go RAM;
- two rigid bodies: one fixed on the tibia, one on the femur;
- a digitizer.

The femoral and tibial rigid bodies were fixed respectively on the femoral shaft and proximal tibia. A dedicated navigation software application was developed for the study and installed in the navigation system. It comprised four steps:

- acquisition of circumduction movement: the navigation system recorded 500 femoral rigid body positions during the circumduction movement;
- acquisition of knee center: medial and lateral condyle positions were acquired by the digitizer; knee center was defined as the middle of both condyles;
- acquisition of ankle center: medial and lateral malleolus positions were acquired by the digitizer; ankle center was defined as the middle of both malleoli;
- acquisition of anatomic hip center: 1000 points were acquired by the digitizer on the femoral head.

Each step was run five times per limb. Anatomic HC acquisition ( $HC_{anat}$ ) was performed with the hip dislocated, and corresponded to the center of the sphere adjusted to the points palpated in step 4. Anatomic referencing of the lower limb  $(O, \vec{i}, \vec{j}, \vec{k})_{Lower\ Limb}$  was determined as:

- origin  $O$  located in the knee center;
- vector  $(i)$ : perpendicular to the transverse plane, oriented according to the vector from knee center to hip center;
- vector  $(j)$ : perpendicular to the sagittal plane, oriented according to the vector from medial to lateral condyle;
- vector  $(k)$ , perpendicular to the frontal plane, defined as the vectorial product of vectors  $(i)$  and  $(j)$ .

### 3.1. Assessment

HC location errors in the in silico experiment were defined as the distance between  $HC_{reference}$  and the four HCs derived from the four algorithms.

Two studies were conducted under the in vitro experiment.

**Table 1**  
Values of the input parameters for the in silico tests.

Tests	Test 1: Camera noise	Test 3: Movement amplitude	Test 4: Number of circumductions	Test 5: Acetabular noise
Movement amplitude (°)	30	10–70 Step: 10	30	30
Number of circumductions	1	1	1–5 Step: 1	1
Camera noise (SD in° for rotation. SD in mm for translation)	Rot.: 0.1–1 Step: 0.1	Rot.: 0.1	Rot.: 0.1	Rot.: 0
	Trans.: 0.5–5 Step: 0.5	Trans.: 0.5	Trans.: 0.5	Trans.: 0
Acetabular noise (SD in mm)	No	No	No	1–10 Step: 1
Number of experiments	1000	1000	1000	1000

SD: standard deviation for the Gaussian noise; Trans.: translation; Rot.: rotation.

3.1.1. Study 1 – HC precision and accuracy

HCs were acquired five times per specimen, and precision was assessed as the scatter of these results for each specimen around the mean HC provided by a given method. Accuracy was assessed by the distance between the anatomic HC and the acquired HCs in each specimen.

3.1.2. Study 2 – Impact on HKA angle

The four HKA angles ( $HKA_{Gamage}$ ,  $HKA_{Halvorsen}$ ,  $HKA_{Pivot}$ ,  $HKA_{LMP}$ ) corresponded to the angles in the frontal plane between the knee and ankle centers and the four HCs according to the four methods. Error was defined as the difference between these HKA angles and the HKA angle determined by the mean anatomic HC.

3.2. Statistical analysis

For a minimum power of 80% with 5% alpha risk, at least 30 measurements per group were required for the in vitro experiment. Differences were assessed with an analysis of variance (ANOVA) and post-hoc Tukey test, with the significance threshold set at 5%.

4. Results

4.1. Accuracy and precision of HC location

The in silico results for the LMP, Pivot, Gamage and Halvorsen methods respectively are presented below. All differences were significant.

4.1.1. Test 1 – Camera noise

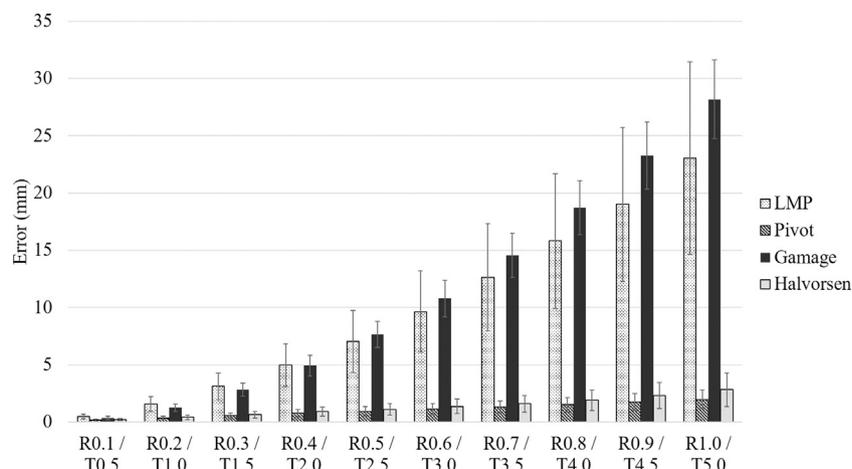
Error was  $0.49 \pm 0.20$  (0.05–1.54) mm,  $0.18 \pm 0.08$  (0.02–0.50) mm,  $0.36 \pm 0.15$  (0.04–0.90) mm and  $0.21 \pm 0.09$  (0.01–0.60) mm for low noise, and  $23.07 \pm 8.40$  (2.10–54.67) mm,  $1.98 \pm 0.81$  (0.15–4.89) mm,  $28.18 \pm 3.42$  (18.57–37.60) mm and  $2.84 \pm 1.46$  (0.11–9.44) mm for high noise level (Fig. 1).

4.1.2. Test 2 – Movement amplitude

Error was  $1.65 \pm 0.72$  (0.13–4.80) mm,  $0.52 \pm 0.22$  (0.05–1.23) mm,  $3.02 \pm 0.57$  (0.60–4.78) mm and  $0.61 \pm 0.27$  (0.04–1.82) mm for low amplitude (Fig. 2), and was  $0.18 \pm 0.08$  (0.01–0.53) mm,  $0.09 \pm 0.04$  (0.01–0.28) mm,  $0.11 \pm 0.05$  (0.01–0.35) mm and  $0.11 \pm 0.05$  (0.01–0.33) mm for high amplitude (Fig. 2).

4.1.3. Test 3 – Number of circumductions

Error was  $0.50 \pm 0.20$  (0.05–1.34) mm,  $0.18 \pm 0.08$  (0.01–0.44) mm,  $0.36 \pm 0.14$  (0.03–0.80) mm and  $0.21 \pm 0.09$  (0.01–0.55) mm for one circumduction movement, and  $0.27 \pm 0.07$  (0.07–0.54)



**Fig. 1.** In silico test 1–HC location error according to camera noise. R and T, respectively in degrees and millimeters, represent noise applied to rigid body orientation and position.

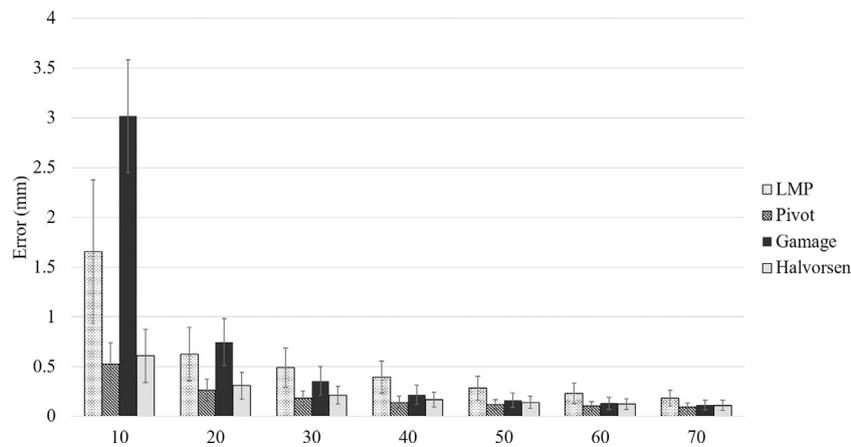


Fig. 2. In silico test 2-HC location error according to movement amplitude (°).

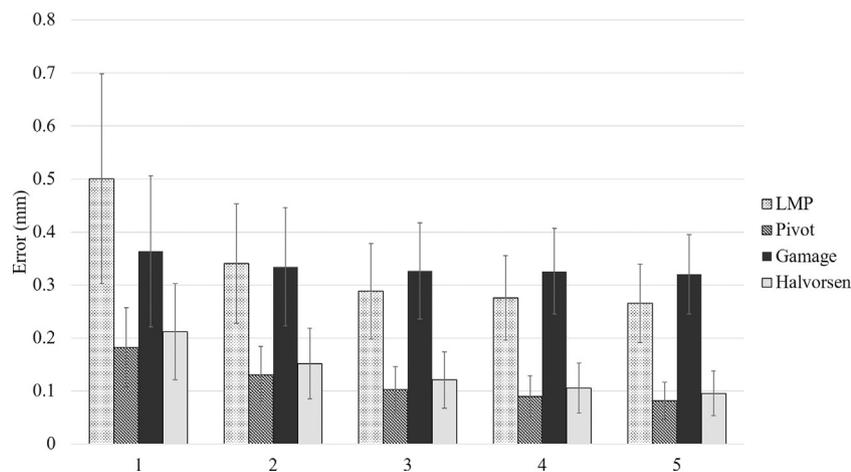


Fig. 3. In silico test 3-HC location error according to number of circumductions.

mm,  $0.08 \pm 0.35$  (0.00–0.21) mm,  $0.32 \pm 0.07$  (0.10–0.54) mm and  $0.10 \pm 0.04$  (0.01–0.25) mm for five circumductions (Fig. 3).

#### 4.1.4. Test 4 – Acetabular noise

Error was  $1.36 \pm 0.79$  (0.05–5.42) mm,  $0.54 \pm 0.27$  (0.01–1.62) mm,  $4.74 \pm 0.59$  (2.82–6.58) mm and  $0.62 \pm 0.28$  (0.04–1.76) mm for low noise (Fig. 4), and  $11.30 \pm 5.77$  (0.56–37.87) mm,  $2.78 \pm 1.47$

(0.10–8.77) mm,  $88.08 \pm 8.85$  (60.59–117.79) mm and  $24.33 \pm 9.82$  (1.40–66.17) mm for high-level noise (Fig. 4).

In the in vitro experiment, the maximal variation in anatomic HC was 0.83 mm. Figs. 5 and 6 show precision and accuracy for the LMP, Pivot, Gamage and Halvorsen methods. Precision was respectively  $8.2 \pm 4.6$  (3.3–23.6) mm,  $7.3 \pm 3.6$  (3.4–14.1) mm,  $33.6 \pm 19.1$  (4.7–111.4) mm and  $35.0 \pm 25.0$  (4.7–132.5) mm,

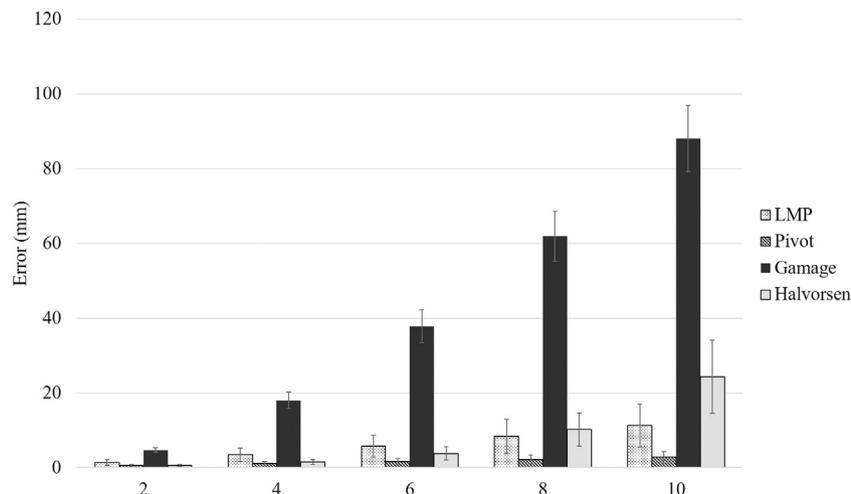
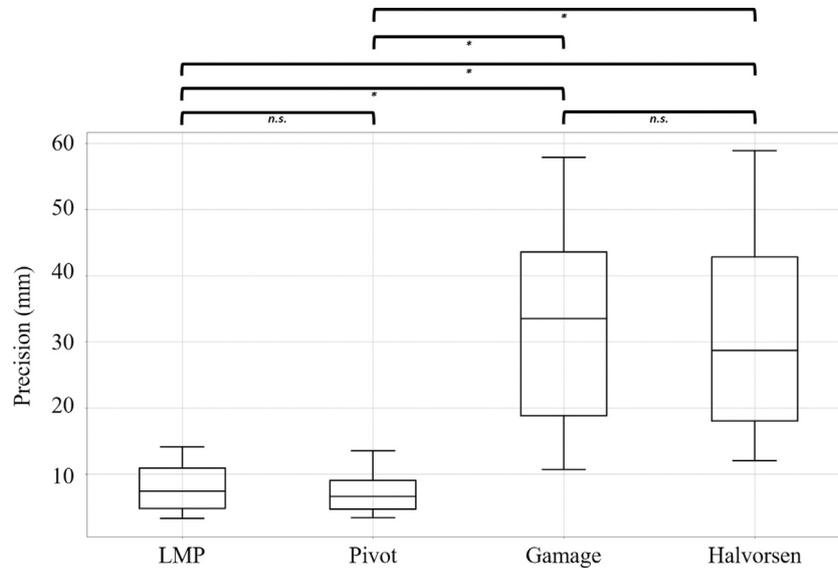
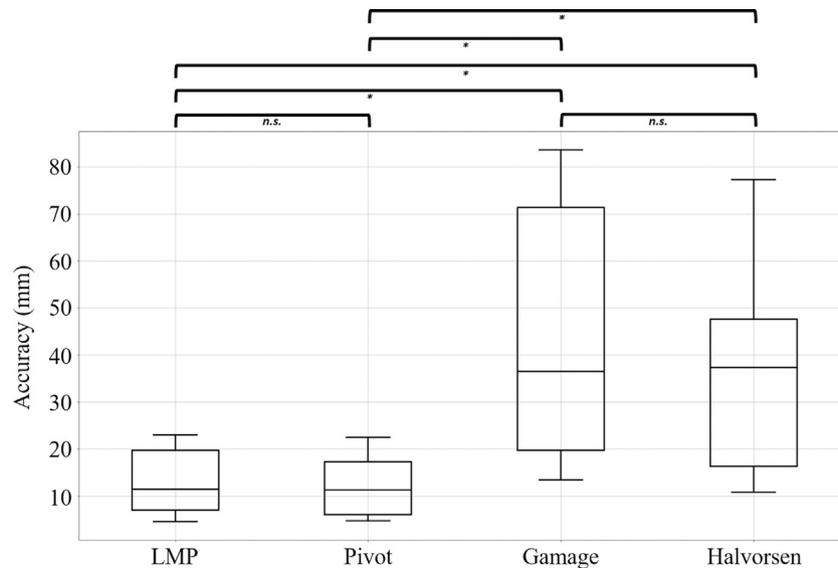


Fig. 4. In silico test 4-HC location error according to acetabular noise (mm).



**Fig. 5.** Hip Center precision on LMP, Pivot, Gamage and Halvorsen methods. (\*) and (n.s.): respectively, significant ( $p < 0.05$ ) and non-significant ( $p > 0.05$ ).



**Fig. 6.** Hip Center location accuracy on LMP, Pivot, Gamage and Halvorsen methods. Accuracy corresponds to distance between estimated and anatomic HCs. (\*) and (n.s.): respectively, significant ( $p < 0.05$ ) and non-significant ( $p > 0.05$ ).

and accuracy  $13.5 \pm 8.2$  (3.2–40.7) mm,  $12.3 \pm 6.4$  (3.2–23.6) mm,  $47.0 \pm 33.3$  (6.2–176.6) mm and  $40.3 \pm 27.8$  (6.1–130.3) mm. Differences were non-significant between the LMP and Pivot methods on the one hand and Gamage and Halvorsen methods on the other (Figs. 5 and 6).

#### 4.2. Error in HKA angle estimation

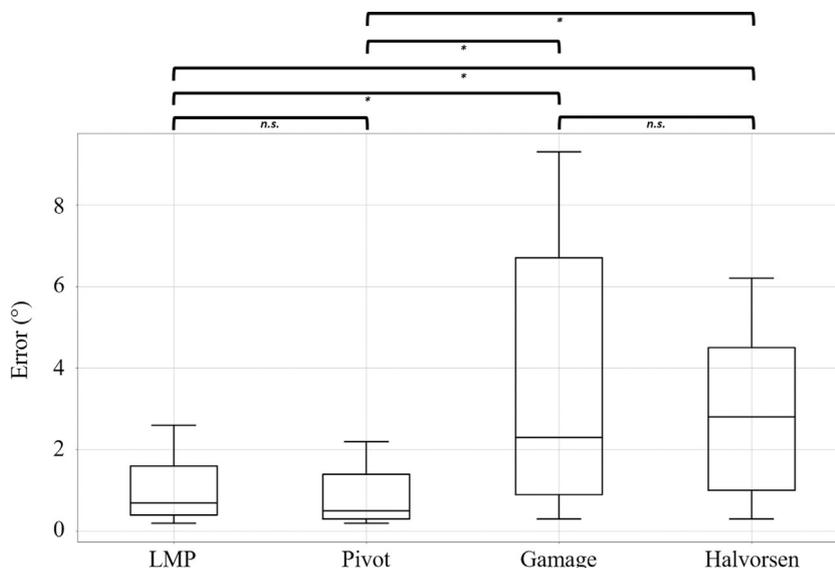
Fig. 7 shows HKA angle estimation error of respectively  $1.1 \pm 0.9^\circ$  (0.1–3.7),  $0.9 \pm 0.8^\circ$  (0.0–2.5),  $3.2 \pm 2.7^\circ$  (0.0–12.7) and  $3.8 \pm 3.5^\circ$  (0.0–13.3) for the LMP, Pivot, Gamage and Halvorsen methods. Differences were again non-significant between the LMP and Pivot methods on the one hand and Gamage and Halvorsen methods on the other (Table 2).

### 5. Discussion

No published studies really assessed and compared several methods of HC location in computer-assisted surgery. We selected

the four most widely used methods (LMP, Pivot, Gamage and Halvorsen) and conducted an in silico and in vitro study to determine whether all four provided equivalent precision and accuracy.

The in silico study assessed the independent influence of four parameters on the precision of the four algorithms. As reported in the literature [3,7,8], the methods proved to be strongly affected by noise inherent to acquisition conditions. Two types of noise were assessed: camera noise, simulating equipment-related imprecision, and acetabular noise, reproducing pelvic movement or femoral head non-sphericity. The LMP and Gamage methods were strongly impacted by both types of noise. The Halvorsen method retained greater accuracy under camera noise but was strongly impacted by acetabular noise. The Pivot method was the most accurate under both types of noise. The impacts of movement amplitude and circumduction number were also analyzed: at least three circumductions are recommended, with at least  $30^\circ$  amplitude. The LMP and Gamage methods were the most impacted by these parameters. The Pivot method was finally the most accurate.



**Fig. 7.** Hip-Knee-Ankle (HKA) angle error on LMP, Pivot, Gamage and Halvorsen methods. (\*) and (n.s.): respectively, significant ( $p < 0.05$ ) and non-significant ( $p > 0.05$ ).

**Table 2**

Post-hoc Tukey test for hip-knee-ankle (HKA) angle estimation:  $p$ -values for the four hip center computation methods.

Methods	LMP	Pivot	Gamage	Halvorsen
LMP		0.9866	0.0031	0.0001
Pivot			0.0010	0.0000
Gamage				0.7413
Halvorsen				

LMP: Least-Moving Point.

The in vitro study assessed and compared the four methods under conditions approximating clinical reality. Five acquisitions were made in each of six cadaveric limbs. Precision, accuracy and HKA angle error were assessed against anatomic HC. Maximum precision in determining anatomic HC was inferior to 1 mm, and was therefore sufficiently low for it to be considered as a reference value. Precision and accuracy were significantly better with the LMP and Pivot methods than with the Gamage or Halvorsen methods, and the same held for HKA angle precision.

The two experiments highlighted differences in results between the four methods of HC location in computer-assisted surgery. Acetabular noise was the factor most strongly impairing results; thus any hip abnormality, such as head non-sphericity disturbing circumduction, osteoarthritis rendering the joint rigid and inducing parasitic pelvic movements, etc., is liable to significantly impair accuracy. None of the study limbs showed such abnormalities; however, the in silico experiment demonstrated that the Pivot method was the most robust in this regard. Likewise, the number of measurements performed in the in vitro experiment did not allow us to identify the best method between the two most accurate ones (Pivot and LMP), but the in silico experiment clearly showed the superiority of the Pivot method.

#### Disclosure of interest

The authors declare that they have no competing interest.

#### Funding

The study received State funding from the National Research Agency under the “Investissements d’Avenir” program (ref. ANR-17-RHUS-0010).

#### Author contributions

Guillaume Dardenne: study design; data acquisition, analysis and interpretation; statistics; experimentation; article writing. Zoheir Dib contributed to study design, data acquisition, analysis and interpretation, statistics, experimentation and article writing. Nicolas Poirier contributed to data acquisition, analysis and interpretation, statistics, experimentation and article writing. Chafiaa Hamitouche contributed to data analysis and interpretation, statistical analysis, experimentation and article revision. Christian Lefevre contributed to data analysis and interpretation, statistical analysis, experimentation and article revision. Eric Stindel designed the study and contributed to data analysis and interpretation, statistical analysis, experimentation and article writing and revision.

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