Cup-To-Neck Contact and Range of Motion after Total Hip Arthroplasty with Large Head Diameters: An Original Three-Dimensional Combined Gait and Videofluoroscopy Analysis

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Abstract: After a total hip arthroplasty, a limited range of motion and lower-limb disability continue to be observed, with these being mainly associated with the implant design and the head-to-neck ratio. Larger diameters of the head bearings were assumed to provide better stability, a larger range of motion, and smaller risks of dislocation and stem-to-liner impingement. However, these claims have never been demonstrated in real patients. The specific aim of this study was to assess, via multi-instrumental analysis, whether the range of motion of a replaced hip is limited by the stem-to-liner contact in patients with large femoral head diameters. Twenty-three patients with a total hip arthroplasty were evaluated at their one-year follow-ups using clinical and instrumental examinations. A combined three-dimensional gait analysis of the full body and videofluoroscopy analysis of the replaced hip were performed during the execution of standard, i.e., daily living, and more demanding motor tasks. The latter were meant to reach the extreme range of motion at the replaced hip site, thus revealing possible stem-to-liner contact. An original technique based on imaging and computer-aided design (CAD) models of the prosthesis components was developed to calculate the stem-to-liner distance. Excellent clinical scores were observed in the study. The gait analysis showed that the range of motion of the replaced hip in the sagittal plane, averaged over all patients, ranged from 28° to 78° in standard activities. In more demanding tasks, single peaks were as high as 110°, 39°, and 60° in the sagittal, frontal, and transverse anatomical planes, respectively. In all motor tasks, the stem-to-liner distances ranged from 8.7 to 13.0 mm on average, with one outlier minimum distance being 2.2 mm. This study shows that, even in demanding motor tasks and with an extreme range of motion, the hip joint replaced with large femoral head diameters did not experience impingement between the prosthesis components.

Keywords: total hip arthroplasty; gait analysis; 3D videofluoroscopy; stem-to-liner impingement; daily living activities
1. Introduction

In the case of severe coxarthrosis, pain and reduced joint function are the most common symptoms. Hence, pain relief and restoration of a physiological range of motion (ROM) are the objectives of a total hip arthroplasty (THA) [1]. Although this surgical procedure has a high success rate [1], particularly in the elderly population [2], a limited ROM at the replaced hip joint and lower-limb disability are still observed [3]. These drawbacks were associated with several critical factors [1,3–5], but among these, the implant design and head-to-neck ratio were considered the most relevant. In particular, these factors seem to affect the hip joint ROM after replacement because of the possible undesired cup-to-neck prosthetic contact, also known as the stem-to-liner (StL) impingement [4,6]. This introduces serious concerns when the indications for a THA are extended to younger patients, i.e., those subjects with a more active and demanding lifestyle, where a replaced hip ROM is expected to be large [7]. To cope with a limited ROM after a THA, prosthesis designs with larger diameter head bearings have been introduced to provide stability, a larger ROM, a smaller risk of dislocation, and to possibly prevent StL impingement. These claims have been supported in the literature [8–12], although concerns are still reported [13–15].

ROM and joint rotation have been extensively investigated in vivo using standard gait analysis (GA) [16–19] and other simple but less accurate instruments, such as goniometers [20,21] and inertial measurement units [18,22,23]. Due to the known technical limitations of these techniques, the ROM at the replaced hip joint is an approximated estimation and the exact cup-to-neck interaction cannot be determined with these instruments. In vitro [24,25] and in silico [26–29] evaluations have thus been performed as well, but these suffer from unrealistic soft tissue arrangements and overall motion and loading conditions. Today, very little is known about the ROM at the replaced hip in large and extreme joint movements. In particular, no accurate three-dimensional (3D) StL distances have been reported; these would be particularly interesting in the presence of large diameter heads, which are claimed to contribute to larger and smoother joint motion. To analyze this critical distance in daily living activities, as well as more demanding activities, a reliable 3D technique for component-to-component interaction is essential. The extent to which a large ROM is achieved and StL impingement is prevented should be assessed in real patients. Both the ROM and StL impingement depend on many conditions, including patient status, prosthesis design, component implantation, and the soft tissues. Careful 3D experimental studies in THA patients are therefore necessary, possibly involving combining full-body motion analyses and imaging at the replaced joint.

Within the currently available techniques, stereophotogrammetry [16] and radiography [30] have potential regarding these in vivo analyses for both ROM and StL interaction analyses. The ROM at the replaced hip in extreme motion exercises has been analyzed to a limited extent [31,32], as well as for StL impingement [6,33], where there is a lack of studies on patients with large diameter heads. Whereas standard GA [34] can be easily adapted for more demanding motor activities, accurate 3D StL interactions can only be addressed using 3D videofluoroscopy analysis (VA). This allows for the reconstruction of the absolute and relative position and orientation of the prosthesis components in 3D by using 2D-to-3D spatial matching [35]. This has been widely adopted for assessing the surface-to-surface interaction of prosthesis components in total joint replacement [35–38] and to a limited extent in THA [39–42]. However, single-plane VA has been demonstrated to be a good compromise between patient safety and measurement accuracy [42]. Rarely, 3D GA and VA have been used in combination, and only in total knee and ankle replacements [36,43,44].

The present in vivo study aimed to assess whether the ROM at the replaced hip joint was limited by the StL contact, i.e., impingement, in THA patients with large head diameters and a large ROM for both active and passive tasks. Toward this aim, 3D GA and VA were used in combination, and an original technique was developed to calculate the StL distance from the latter technique. Different head diameters of the prostheses were also analyzed to assess the extent to which a larger diameter may result in a larger ROM and a smaller risk of impingement in extreme arcs of hip joint motion.
2. Methods

2.1. General Information

Twenty-five patients affected by coxarthrosis were recruited in the present study and underwent cementless THA surgery. The relevant inclusion criteria were: unilateral primary or secondary hip arthritis with indicators that allowed for a THA, aged between 35 and 55 years, a body mass index (BMI) less than 30, a full comprehension of the investigation protocol, and a signature of informed consent. In contrast, pregnant women and patients with contralateral hip arthritis, neurological disorders, and other lower limb pathologies were excluded. Before the operation, clinical assessments were performed using the Harris Hip [45], the University of California at Los Angeles (UCLA) [46,47], Oxford Hip [48], and the Western Ontario and McMaster Universities Osteoarthritis (Womac) [49] score systems. After surgery, at the 12-month follow-up, all patients were contacted for post-operative control. Twenty-three out of the initial 25 patients agreed to be examined at the follow-up and are reported in Table 1. The follow-up control consisted of clinical assessments using the same scoring systems and instrumental functional evaluations via 3D GA and VA to assess the ROM and StL interaction, respectively, at the replaced hip.

Table 1. Demographical data. The total number of female (F) and male (M) participants, as well as the total left (L) and right (R) operated knee sides, are reported in the last row, along with the mean ± standard deviation values for all patients when appropriate. BMI: Body Mass Index.

| No | Head Diam. | Gender | Age (years) | Weight (kg) | Height (cm) | BMI | Operated Side |
|----|------------|--------|-------------|-------------|-------------|-----|---------------|
| 1  | 40         | F      | 52.4        | 72          | 170         | 24.9| L             |
| 2  | 40         | F      | 57.4        | 80          | 165         | 29.4| L             |
| 3  | 28         | M      | 48.2        | 69          | 171         | 23.7| L             |
| 4  | 40         | M      | 53.3        | 105         | 192         | 28.5| L             |
| 5  | 36         | M      | 55.9        | 95          | 171         | 32.5| L             |
| 6  | 36         | F      | 53.7        | 68          | 160         | 26.6| R             |
| 7  | 40         | F      | 46.0        | 56          | 164         | 20.8| L             |
| 8  | 36         | F      | 22.8        | 56          | 154         | 23.6| R             |
| 9  | 40         | M      | 54.4        | 85          | 178         | 26.8| L             |
| 10 | 40         | M      | 51.0        | 88          | 174         | 29.1| L             |
| 11 | 40         | M      | 52.6        | 80          | 160         | 31.3| R             |
| 12 | 28         | F      | 33.6        | 46          | 154         | 19.4| L             |
| 13 | 40         | M      | 49.8        | 71          | 168         | 25.2| L             |
| 14 | 40         | M      | 53.2        | 80          | 160         | 31.3| L             |
| 15 | 40         | M      | 36.1        | 88          | 179         | 27.5| L             |
| 16 | 28         | F      | 45.0        | 64          | 165         | 23.5| R             |
| 17 | 40         | M      | 53.5        | 72          | 168         | 25.5| L             |
| 18 | 36         | F      | 53.7        | 62          | 160         | 24.2| L             |
| 19 | 28         | F      | 52.9        | 50          | 157         | 20.3| R             |
| 20 | 40         | F      | 56.0        | 64          | 165         | 23.5| R             |
| 21 | 36         | F      | 45.9        | 60          | 152         | 26.0| R             |
| 22 | 28         | F      | 56.8        | 78          | 155         | 32.5| L             |
| 23 | 36         | F      | 47.4        | 64          | 160         | 25.0| R             |

Overall 36.3 ± 4.8 13 F/10 M 49.2 ± 8.3 71.9 ± 14.6 195.3 ± 9.5 26.1 ± 3.7 14 L, 9 R

This study was approved by the ethical committee of the Istituto Ortopedico Rizzoli - Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS), Bologna, Italy (Prot. Gen 0007327, 1 March 2013; per amendment, Prot. Gen 0043507, 24 December 2015), and informed consent was provided and signed by all patients before surgery. Relevant data is held in the clinicaltrials.gov repository (identification number: NCT02047292).

2.2. Surgical Procedure

All THA operations were performed by the same surgeon via a direct lateral approach [50], targeting the standard Lewinnek’s “safe zone” [51]. Eligible patients were all implanted with the same
Corail® femoral stem; the acetabular cup systems were Delta Motion® (36 and 40 mm head diameter sizes) and the Pinnacle® (28 mm head diameter) (Table 1). These THA systems were all made by DePuy® Synthes (Warsaw, IN, USA). Regarding the Delta Motion® system, developed for larger head diameters, the 36 and 40 mm diameters were selected for some patients in this study based on the relevant patient’s hip joint dimensions, as assessed using X-ray images; for small hips, the 28 mm Pinnacle® system was implanted since the acetabular cup with this head diameter was not available in the Delta Motion® system.

2.3. Instrumental Analyses at Follow-Up

2.3.1. Gait Analysis

At twelve months after surgery, patients had their gaits analyzed (Figure 1) using an eight-camera motion capture system (Vicon®, Oxford, UK) combined with two force platforms (Kistler®, Winterthur, Switzerland). Simultaneously, a wireless electromyographic system (EMG; ZeroWire®, Aurion, Milan, Italy) with a 2000 Hz sampling frequency was used to record the myoelectric activity of the main lower limb muscles: gluteus maximus (GMAX), gluteus medialis (GMED), rectus femoris (RF), great adductor (ADD), vastus medialis (VML), vastus lateralis (VL), and long head of the biceps femoris (BFLH). These surface dynamic electromyographic signals were automatically processed using a custom single threshold algorithm to obtain the on–off patterns of the corresponding muscle activity. Relevant motion data collections were performed during the execution of several standard and more demanding motor tasks. For the former, the following were analyzed: walking, sit to stand from a chair, stair climbing, and stair descending. For the latter, i.e., those exercises potentially reaching extreme hip ROM arcs and thus revealing possible StL contact, the following were analyzed: tailor sitting, lunge forward, high step (i.e., hyperflexion) and lunge backward (i.e., hyperextension) using the operated-on leg, and a full double-leg squat. The patients were equipped with instrumentation with an appropriate marker-set according to an established protocol for segment and joint motion analysis [34,52]. This involved a total of 36 spherical 15 mm diameter reflective markers that were stuck on the skin that corresponded to relevant palpable anatomical landmarks on the pelvis and lower limb segments. These markers were tracked in space using the camera system at 100 Hz during each motion data collection. From the external skin markers, joint centers and anatomy-based reference frames were determined for each bone, and these were used to calculate the joint rotations in the three anatomical planes according to international standards [53]. During the data acquisition of standard motor tasks, i.e., those that are typical for daily living activities, the ground reaction force was also collected using the two force platforms to also calculate joint moments in the three anatomic planes. The time history of these kinematic and kinetic variables was reported as a percentage of the normalized motion cycle; for level walking only, these patterns were superimposed to corresponding control bands from a population of healthy subjects [34,52].
2.3.2. Videofluoroscopy Analysis

Immediately after the GA, the patients underwent 3D VA evaluations [35,37]. These consisted of static X-ray image acquisitions of the replaced hips using a standard fluoroscope (digital remote-controlled diagnostic Alpha90SX16, CAT Medical System, Monterotondo, Italy). Patients were asked to repeat the more demanding motor tasks that were performed in the GA; for each of these, a single image was acquired once the extreme position for the joint was reached and the instrumental field of view was well-centered on the replaced hip joint. A standard frontal and sagittal image were also acquired with the patient in a double-leg upright position.

Data processing was done using a semi-automatic 2D-to-3D iterative shape-matching technique [35,43], which involved superimposing a 2D projection of the 3D computer-aided design (CAD) model of the two THA components into the images collected from the patients (Figure 2). The technique can reconstruct 3D poses of the prosthetic components within 0.5 mm and 1.0° accuracies [35]. These 3D poses were used to calculate the StL distance, which was defined as the minimum distance between the liner border of the acetabular cup and the relevant section of the neck of the femoral stem, i.e., at the intersection between this neck and the virtual sphere embedded in the liner. These calculations were performed in Matlab (software release 2016a on 64-bit for windows; The MathWorks, Inc., Natick, MA, USA).

Figure 1. Images from the motor tasks performed for the gait analysis (GA), with the relevant acquisition set-up: (A) Walking, (B) Chair raising/sitting, (C) Stair climbing, (D) Stair descending, (E) Squat, (F) High step flexion, (G) Tailor sitting, (H) Lounge forward and (I) Lounge backyard.
2.4. Statistical Analysis

To achieve a proposed power of 80% and an $\alpha$ level of 0.05, a sample size of at least 25 hips was needed to derive differences in the clinical scores between pre-op and post-op according to the recent relevant literature [12,54]. Particularly, paired $t$-tests were performed to identify any significant differences in the clinical scores and the corresponding $p$-values were calculated for assessing the significance, with this being accepted as $p < 0.05$. Correlation analyses were carried out to identify any significance, with this being accepted as $p < 0.05$, between the StL distances and the implanted femoral head diameter. All statistical calculations were performed in MatLab (software release 2016a on 64-bit for windows; The MathWorks, Inc., Natick, MA, USA).

3. Results

3.1. General Overview

The overall methodology combining the GA- and VA-based 3D analyses was applied successfully to the present population, showing that the patients were able to achieve very large ROMs at the replaced hip during the follow-up. The more demanding tasks for the extreme hip ROM, which were performed to possibly reveal an StL contact, were effectively replicated in the GA laboratory and in the VA room. Originally, the StL distance was calculated and checked visually on the computer using the prosthesis component models.

3.2. Clinical and Radiological Examinations

Excellent clinical scores were observed at the follow-ups. The Harris Hip, UCLA, and Oxford scores significantly increased from pre-op to post-op by $52.2 \pm 7.5$, $6 \pm 1.5$, and $46.2 \pm 2.0$ points ($p < 0.05$) on average, respectively; the Womac score dropped significantly by $84.0 \pm 5.0$ points ($p < 0.05$), confirming the excellent outcome. Radiological examinations confirmed the cup positionings to be within the targeted $10–25^\circ$ of anteversion and $35–45^\circ$ of inclination.
3.3. Instrumental Analyses at Follow-Up

From the GA, an overall good recovery of normal walking patterns was observed for the standard motor tasks in terms of the kinematics, kinetics, and EMG when compared to the reference for normality [34] (Figure 3). The ROM at the replaced hip in the sagittal plane ranged from 28° to about 80° on average (the top three tasks of Figure 4 and the top four tasks in Table 2), as observed in the stair descending and chair raising/sitting tasks, respectively. During these tasks, in the other two anatomical planes, the patterns of hip rotation were still consistent, but with a ROM smaller than 26°.

In the more demanding motor tasks (the rest of the tasks in Figure 4 and Table 2), the sagittal plane ROM was generally larger than 71° on average, with a maximum of almost 86° observed in the high step flexion. Joint rotation peaks relative to the neutral alignment were generally observed in the hip flexion, abduction, and internal rotation directions, except for in the backward lunge where these were all observed in the opposite directions. The backward lunge showed an ROM of only 25° on average, but this exercise only utilized hip joint extension. A large ROM was also observed in the other two anatomical planes, with the largest at nearly 29° occurring during high step flexion.

In each of the standard and demanding motor tasks, consistent patterns of hip joint rotations over the patients were observed, as depicted by the dimensions of the bands; this strengthened the present results because it shows that extreme motion arcs were reached by the patients in all three anatomical planes.

In all the demanding motor tasks, the StL distances from the 3D VA (Table 3) ranged from about 9 to 13 mm on average, with the smallest being observed in high step flexion. StL contact was experienced in none of the patients assessed; the smallest distance for all patients and all tasks was 2.2 mm.

A statistically significant correlation between the ROM and head diameter was not found in any of the motor tasks analyzed.
Figure 3. The time-history of the main gait variables from the GA during level walking. Joint rotations (left) and moments (right) from these patients (blue) are reported as the mean plus one standard deviation bands for all patients superimposed onto the corresponding bands from the control population. Electromyographic signals from the muscle activation are also reported for a single typical patient (bottom) along with the corresponding physiological timing on the horizontal axis: gluteus maximus (GMAX), gluteus medialis (GMED), rectus femoris (RF), great adductor (ADD), vastus medialis (VML), vastus lateralis (VL), and long head of the biceps femoris (BFLH).
Table 2. Absolute range of motion (ROM, in °) and related peak values relative to the neutral joint alignment, i.e., 0°, for the three anatomical planes (columns) for each of the analyzed motor tasks in the GA; the mean ± standard deviation over the patients, along with a range of (min ÷ max) values, are shown.

| Motor Tasks          | Sagittal       | Frontal        | Axial          |
|----------------------|----------------|----------------|----------------|
|                      | ROM            |                |                |
| Walking              | 37.1 ± 7.6     | 10.5 ± 3.1     | 10.1 ± 4.0     |
|                      | (1.9 ÷ 48.6)   | (5.6 ÷ 17.3)   | (4.2 ÷ −18.7)  |
|                      | 25.9 ± 8.0     | 7.6 ± 3.6      | −1.8 ±10.2     |
|                      | (8.9 ÷ 45.2)   | (1.0 ÷ 16.2)   | (−20.5 ÷ 14.9) |
|                      | 53.0 ± 6.2     | 12.0 ± 5.2     | 14.8 ± 5.6     |
|                      | (42.0 ÷ 63.6)  | (3.6 ÷ 24.4)   | (6.4 ÷ −23.9)  |
|                      | 54.3 ± 8.3     | 8.7 ± 5.7      | 2.5 ± 11.0     |
|                      | (32.8 ÷ 68.3)  | (0.8 ÷ 20.9)   | (−19.9 ÷ 21.6) |
|                      | 27.6 ± 6.1     | 11.5 ± 3.4     | 13.2 ±4.0      |
|                      | (15.0 ÷ 43.1)  | (6.3 ÷ 19.2)   | (8.0 ÷ −22.0)  |
|                      | 32.8 ± 8.3     | 8.2 ± 4.9      | −1.3 ±10.6     |
|                      | (20.1 ÷ 54.2)  | (1.0 ÷ 21.4)   | (−18.0 ÷ −17.1) |
|                      | 78.4 ± 10.2    | 8.8 ± 4.6      | 26.1 ±12.5     |
|                      | (56.2 ÷ 97.4)  | (2.6 ÷ 20.7)   | (8.7 ÷ −48.7)  |
|                      | 78.0 ± 8.5     | 0.2 ± 5.0      | 13.3±14.5      |
|                      | (61.2 ÷ 94.9)  | (−8.2 ÷ 13.2)  | (−12.1 ÷ −40.9) |
|                      | 70.4 ± 16.2    | 10.4 ± 5.8     | 23.5±13.7      |
|                      | (39.7 ÷ 107.5) | (2.8 ÷ 20.6)   | (4.9 ÷ −54.5)  |
|                      | 73.7 ± 12.7    | 1.2 ± 5.5      | 14.7±14.6      |
|                      | (53.0 ÷ 96.8)  | (−13.8 ÷ 9.4)  | (−10.9 ÷ −49.2) |
|                      | 86.4 ± 12.3    | 18.2 ± 6.7     | 29.4±15.9      |
|                      | (63.9 ÷ 110.2) | (8.0 ÷ 34.7)   | (10.2 ÷ 59.7)  |
|                      | 87.4 ± 11.0    | −12.8 ± 7.1    | 17.7±16.2      |
|                      | (66.8 ÷ 106.0) | (−28.0 ÷ 1.1)  | (7.5 ÷ −52.4)  |
|                      | 1.9 ± 1.4      | 1.9 ± 2.0      | 2.1±1.5        |
|                      | (0.3 ÷ 5.3)    | (0.2 ÷ 8.9)    | (0.1 ÷ −6.0)   |
|                      | 73.8 ± 11.3    | 4.2 ± 8.5      | 4.8±13.4       |
|                      | (46.1 ÷ 91.8)  | (−13.1 ÷ 21.0) | (−26.6 ÷ 25.8) |
|                      | 71.0 ± 15.8    | 18.8 ± 7.4     | 23.7±10.6      |
|                      | (33.2 ÷ 99.0)  | (7.1 ÷ 39.3)   | (9.1 ÷ −44.5)  |
|                      | 73.0 ± 13.7    | 9.5 ± 7.1      | 12.5±15.1      |
|                      | (40.0 ÷ 98.4)  | (−0.7 ÷ 22.8)  | (−12.1 ÷ 38.7) |
|                      | 24.9 ± 7.5     | 16.8 ± 8.8     | 18.7±11.4      |
|                      | (13.8 ÷ 44.1)  | (2.7 ÷ 36.8)   | (6.9 ÷ −58.9)  |
|                      | −15.0 ± 7.4    | −11.0 ± 8.3    | −21.9±10.2     |
|                      | (−30.9 ÷ 19.9) | (−32.6 ÷ 3.0)  | (−47.1 ÷ −7.6) |
Figure 4. Patterns of the joint rotation at the replaced hip in the three anatomical planes (columns) for each of the motor tasks in the GA. Bands are the same as in Figure 3.
Table 3. Stem-to-liner (StL) distance (in mm) from the 3D VA; the mean ± standard deviation value from all patients, along with (min ÷ max) values, are shown.

| Motor Tasks      | StL Distance |
|------------------|--------------|
| Squat            | 11.4 ± 6.1   |
|                  | (5.2 ÷ 21.9) |
| High step flexion| 8.7 ±5.2     |
|                  | (2.3 ÷ 17.3) |
| Tailor sitting   | 13.0 ± 5.9   |
|                  | (2.2 ÷ 19.8) |
| Lunge forward    | 11.8 ±5.1    |
|                  | (3.0 ÷ 19.6) |
| Lunge backward   | 11.9 ±5.4    |
|                  | (2.3 ÷ 21.6) |

4. Discussion

For the first time, 3D analyses based on state-of-the-art GA and VA were combined successfully to assess a representative THA population. The overall scope was to measure the patterns and extremes of motion in standard and demanding motor tasks in terms of the ROM and peak rotations in the three anatomical planes at the replaced hip, as well as measure the corresponding StL distance. The THAs were successful and the patients had very good clinical results at the follow-up; therefore, the present observations do represent a realistic picture of the StL interaction in the worst case scenario. GA confirmed that standard motor tasks, i.e., those typical of daily living, do not require a large ROM at the replaced hip, and that very large joint rotations were instead reached in those tasks that were particularly demanding. Nevertheless, no StL contact was measured in any patient in any of these tasks; therefore, it can be deduced that the limits of the ROM after a THA was associated with the soft tissues rather than to the StL impingement.

3D GA- and VA-based evaluations provided accurate and original findings regarding the overall segment and joint motion and the possible StL contacts, i.e., prosthetic cup-to-neck contact. In general, successful THAs were observed for all implanted femoral heads, with these including those usually considered to have large diameters. In this context, GA revealed a good overall functional recovery and very large hip joint rotations in all three anatomical planes for both the standard and demanding motor tasks. Despite these large rotations, the StL distances calculated using VA were all found to be large enough to exclude this contact after considering the instrumental errors. Additionally, there was a clear trend for larger ROMs and smaller cut-to-neck distances for the larger head diameters.

The present novel technique of the StL distance calculation deserves a few considerations. This technique is based on established techniques of prosthesis component pose estimation, even during motion, which relies on good quality 2D fluoroscopy images and relevant detailed 3D CAD models. This technique was originally established for knee joint replacements [35,44] and has recently been extended to THAs [33,40–42], though for a limited number of motor tasks. The large amount of literature in this area shows that the overall accuracy is smaller than 1 mm and 1°, which is good enough for the conclusions of this study.

Of interest to physicians and designers involved in THAs is the information about the anatomical plane and the extent to which additional joint motion is necessary to get the real StL final impingement from the measured extreme positions. In other words, it would be very interesting to work out how far these replaced joints were from contact with the prosthesis components. To investigate this, careful computer simulations would be necessary: starting from the CAD models and the absolute and relative positions of the two prosthesis components in the three anatomical planes, further known rotations at the components should be applied to the models until contact is achieved, where this should be done in several different combinations of motion in the three planes. This is a complex exercise,
which is expected to require significant effort; therefore, it should be assigned to possible future work. The results of the present study excluded component-to-component contact but relevant in-depth analysis revealed a positive trend between the head diameter size and StL distance in all motor tasks, though it was not statistically significant; generally, this trend was clearer in the more demanding motor tasks.

Comparison with the relevant literature revealed an overall good superimposition of the present ROM at the replaced hip joints with those reported in similar GA studies [18,22,55,56] reporting evaluations during walking, stair ascending/descending, squatting, and sitting, as well as extreme joint motion. However, different from the present study, these studies did not include THAs with large femoral head diameters and relevant evaluations were conducted during the execution of a more limited number of motor tasks, i.e., those related to standard activities of daily living, and thus, not forcing the replaced joint toward the extremes of motion. As for the component-to-component contact, the present StL distances concurred well with those reported in similar VA-based studies [33,40]; however, again, these studies were not evaluating THAs with large diameters and were limited to chair rising and squatting motor tasks.

Several limitations are present in this study. Only a small number of motor tasks were tested, and other extreme joint positions, particularly involving critical combinations of rotations in the three anatomical planes, may still result in StL contact. However, those motor tasks analyzed here are tasks that can be more frequently experienced in standard conditions of daily living; therefore, analysis of these motor tasks is possibly more critical than analyzing special exercises in exceptionally performing THA patients. In addition, due to the specific dynamics of walking, chair rising/sitting, and stair climbing and descending, the hip joint could not be tracked using VA since this was out of the field of view for most the image collection time. Despite this, several ROM values, along with the associated peaks and StL distances observed, concurred with those reported in other similar GA- [18,22,55] and VA- [33,40] based studies. Another limit of the present StL interaction analysis is that the acetabular cup position is known to play a major role. However, the exact estimation of this in these patients would have required additional imaging of the pelvis, and we, together with the consulted ethics committee, decided not to perform this. Another limitation is that the StL distance was calculated using VA, whereas the ROM and peak joint rotations were found using GA; however, one session immediately followed the other, and the same tools (chairs, steps, etc.) were used. Furthermore, in the VA, static postures were analyzed, and in GA, complete cycles of movement were collected, but the instructions to the patient and visual inspection facilitated the consistent performance of these tasks. Finally, the population size was not large but it is very revealing that the patterns of motion were highly consistent over the subjects (Figures 3 and 4), and that not a single StL contact was achieved in any patient in any task (Table 3).

In conclusion, this multi-instrumental analysis combining GA- and VA-based examinations revealed that, even for demanding motor tasks with extreme ranges of motion, the hip joints replaced with large femoral head diameters did not experience impingement between the prosthesis components. This is important regarding prosthesis design and rehabilitation for THA.

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