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# Simulation of hip bony range of motion (BROM) corresponds to the observed functional range of motion (FROM) for pure flexion, internal rotation in deep flexion, and external rotation in minimal flexion-extension – A cadaver study

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ABSTRACT

*Background:* The study investigated the relationship between computed bony range of motion (BROM) and actual functional range of motion (FROM) as directly measured in cadaveric hips. The hypothesis was that some hip movements are not substantially restricted by soft tissues, and therefore, computed BROM for these movements may effectively represent FROM, providing a reliable parameter for computational pre-operative planning.
*Methods:* Maximum passive FROM was measured in nine cadaveric hips using optical tracking. Each hip was measured in at least ninety FROM positions, covering flexion, extension, abduction, flexion-internal rotation (IR), flexion-external rotation (ER), extension-IR, and extension-ER movements. The measured FROM was virtually recreated using 3D models of the femur and pelvis derived from CT scans, and the corresponding BROM was computed. The relationship between FROM and BROM was classified into three groups: close (mean difference<5°), moderate (mean difference 5–15°), and weak (mean difference>15°).
*Results:* The relationship between FROM and BROM was close for pure flexion (difference = 3.1° ± 3.9°) and IR in deep (>70°) flexion (difference = 4.3° ± 4.6°). The relationship was moderate for ER in minimal flexion (difference = 10.3° ± 5.8°) and ER in minimal extension (difference = 11.7° ± 7.2°). Bony impingement was observed in some cases during these movements. Other movements showed a weak relationship: large differences were observed in extension (51.9° ± 14.4°), abduction (18.6° ± 11.3°), flexion-IR at flexion<70° (37.1° ± 9.4°), extension-IR (79.6° ± 4.8°), flexion-ER at flexion>30° (45.9° ± 11.3°), and extension-ER at extension>20° (15.8° ± 4.8°).
*Conclusion:* BROM simulations of hip flexion, IR in deep flexion, and ER in low flexion/extension may be useful in dynamic pre-operative planning of total hip arthroplasty.

## 1. Introduction

It is important to optimise the biomechanical reconstruction of the hip during Total Hip Arthroplasty (THA) to minimise the risk of complications and patient dissatisfaction. It is therefore standard practice to perform pre-operative planning to help surgical decision making around implant selection and positioning. Planning is becoming increasingly advanced, having progressed from simple physical transparent templates to digital 2D templates, 3D planning using CT, and most recently to 'dynamic 3D planning', with simulation of hip movements. This enables the surgeon to confirm precise restoration of version, leg length and offset, and to move the planned hip into functional positions, to check for problems such as impingement or edge loading [1–4]. These are critical post-THA complications that can result in poor function (such as limping and ongoing pain), and premature implant failure such as implant loosening, dislocation, and excessive wear of the implanted

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joint surfaces, ultimately leading to the need of revision surgery [4,5].

While such dynamic pre-operative planning makes logical sense and is appealing, it is critical that any simulated movements must reflect the way the patient's hip actually moves. It is known that the normal range of movement (ROM) of the hip joint is highly variable between individuals [6,7], and therefore, simulating arbitrary movements taken from the literature is of limited value. If the movements simulated do not correspond with the individual's own normal pre-arthritic ROM, this could be quite misleading, and result in poor planning decisions. It is logical, therefore, to only simulate movements relevant for the individual patient, if they can be determined pre-operatively.

One approach to this is to directly measure a patient's hip movements during different functional activities. However, clinical examination is imprecise and subjective. Motion capture in a gait lab is more accurate, but is not widely available, and may not be practical in patients with a painful hip. It was recently reported that soft tissue artefact (STA) can significantly affect the kinematics captured using skin marker-based motion capture systems, often leading to an underestimation or overestimation of the hip's range of motion [8]. The OPS® system from Corin factors in the relative positions of the pelvis and femur on pre-operative seated and standing lateral radiographs to drive a motion simulation of the patient rising from a chair [4]. The hip movements during this activity are known to be highly variable between individuals, due in part to the influence of the spine [4,9]. However, it is not currently possible to directly measure the normal range of a comprehensive set of functional hip movements pre-operatively for a patient with a joint that is usually stiff and painful. Another method is therefore needed to determine a personalised set of movements for dynamic planning. One such method is to infer the theoretical normal ROM from the patient's own anatomy. It is reasonable to assume that the normal bony anatomy is related to the normal hip ROM that was possible before the onset of arthritis. For many patients with hip arthritis, normal hip anatomy can be determined from CT: they may not have any significant osteophytes or deformity, the contralateral hip may be normal, or historical CT images may be available.

Such a method to determine this theoretical ROM has recently been described in Palit et al. [10]. The bony anatomy is segmented from CT imaging and reconstructed into a patient-specific 3D model of the femur and pelvis. This virtual hip can then be moved in all potential directions to the point of bony impingement to determine a patient-specific bony range of movement (BROM) envelope [10]. It is clear, however, that BROM is an oversimplification, as the actual functional range of motion (FROM) of a hip is further limited by soft tissues and ligaments, either by causing additional impingement, or by acting as a tether. Previous cadaver studies have demonstrated the particular roles of the labrum [11,12], joint capsule [13–15], ligamentum teres [11], iliofemoral ligament [16,17] and intact soft-tissue [18] on hip FROM. All these studies were purely experimental, and either a motion capture system or testing rig was used to measure hip FROM. A few studies measured the effect of soft-tissue impingement intra-operatively during posterior approach THA [19], and anterolateral approach THA [20] using CT-based or imageless navigation system respectively. Other research studies focused on the hip ROM analysis with different conditions such as (a) normal vs post THA [21,22] and (b) normal vs femoroacetabular impingement (FAI) [9,23] for the controlled group patients using motion capture system. Although these studies provided greater insight about the effect of soft tissue and ligaments on hip FROM for various conditions and manoeuvres, it did not directly compare the measured FROM with the simulated BROM. There are limited number of publications where the measured hip FROM was combined with simulated hip motions. Woerner et al. [20] measured hip FROM intra-operatively during anterolateral THA whereas Noble group [24,25] measured the FROM using cadaver hips. Woerner et al. [20] registered the measured FROM to the CT coordinate for BROM analysis using the reference pins that were attached on the skin surface near to the bony landmarks [20]. Due to the skin artefact, this registration process was not very accurate. Also, only 6 hip motions were considered, and these motions were for a replaced hip instead of a healthy hip. Incavo et al. [24] combined experimental FROM measurement with hip motion simulation to compare between two processes: THA and surface replacement arthroplasty (SRA). Recently, Han et al. [25] and Palit et al. [26] compared the simulated BROM with measured FROM. Both studies reported that certain movements, like hip extension, are primarily limited by soft tissues, whereas in other movements, such as flexion, soft tissue constraints are relatively minimal [25]. However, these studies only considered seventeen [25] and seven [26] FROM positions that was not sufficient to perform a comprehensive analysis to explore the relationship between FROM and BROM for different hip positions.

The purpose of this study, therefore, is to investigate the relationship between a simulated BROM and the normal FROM of the hip. To achieve this, cadaveric hips without evidence of disease were used. For each hip a CT was performed, from which the theoretical BROM envelope could be determined. The FROM of each hip was also determined using a navigation system, which tracked the relative positions of the femur and pelvis as the hip was moved passively to the maximum range in multiple extreme positions. These positions were then compared with the theoretical BROM boundary, to determine the difference between them. The hypothesis is that because some hip movements are less constrained by the soft tissues, the predicted BROM for these movements would be similar to the measured FROM and could therefore be used as valid subject-specific parameters for the dynamic pre-operative THA planning.

## 2. Methods

### 2.1. Specimen preparation and experimental set-up

Eight cadaveric specimens, transected from the L5 vertebra to the feet, were used in the experimental study. X-rays were conducted to screen for signs of arthritis and other pathological conditions to ensure that the measurements were exclusively taken from hips without relevant pathology or abnormality: only 9 hips met these criteria. The reasons for excluding the remaining hips were the presence of significant osteophytes (2 hips), femoral neck fracture (1 hip), previous hip arthroplasty (1 hip), and previous below-knee amputation (4 hips). The study was approved by Research and Development, University Hospitals Coventry and Warwickshire (UHCW) NHS Trust (Ref: GF0503), and Biomedical & Scientific Research Ethics Committee (BSREC) at University of Warwick (ref: BSREC 66/22–23).

Measurement of passive hip FROM was performed with an AICON MoveInspect XR8 system (AICON, Hexagon, UK) (Fig. 1a). The cadaver specimen was placed on a specifically designed fixation plate to securely hold the pelvis during the passive femoral movements. A dome-shaped 'femoral adaptor' was attached to the distal femoral shaft, and a 'pelvis adaptor' was attached to the iliac crests (Fig. 1A) using surgical pins, external fixation clamps (Hoffman 3, Stryker®), and plastic glue. Metrological graded 'Reference Spheres' (Alufix, reference ball id 28403-1, 18 mm diameter, Aluminium) were attached to the distal femoral bone and pelvis (Fig. 1A). The centre points of these spheres served as reliable points of reference for accurate data registration of the measured FROM onto the BROM simulation. A detailed experiment set-up was described by Palit et al. [26].

### 2.2. Measurement of FROM

Following the calibration of the AICON MoveInspect XR8 system, the surface points of pelvis and femur reference spheres were measured using a touch probe to determine their centres. Initial measurement was performed to find the positional relations between (a) femoral adaptor and femur reference spheres, and (b) pelvis adaptor and pelvis reference spheres. Thereafter, measurements were performed once femur had been passively moved manually to the end of its range as assessed by

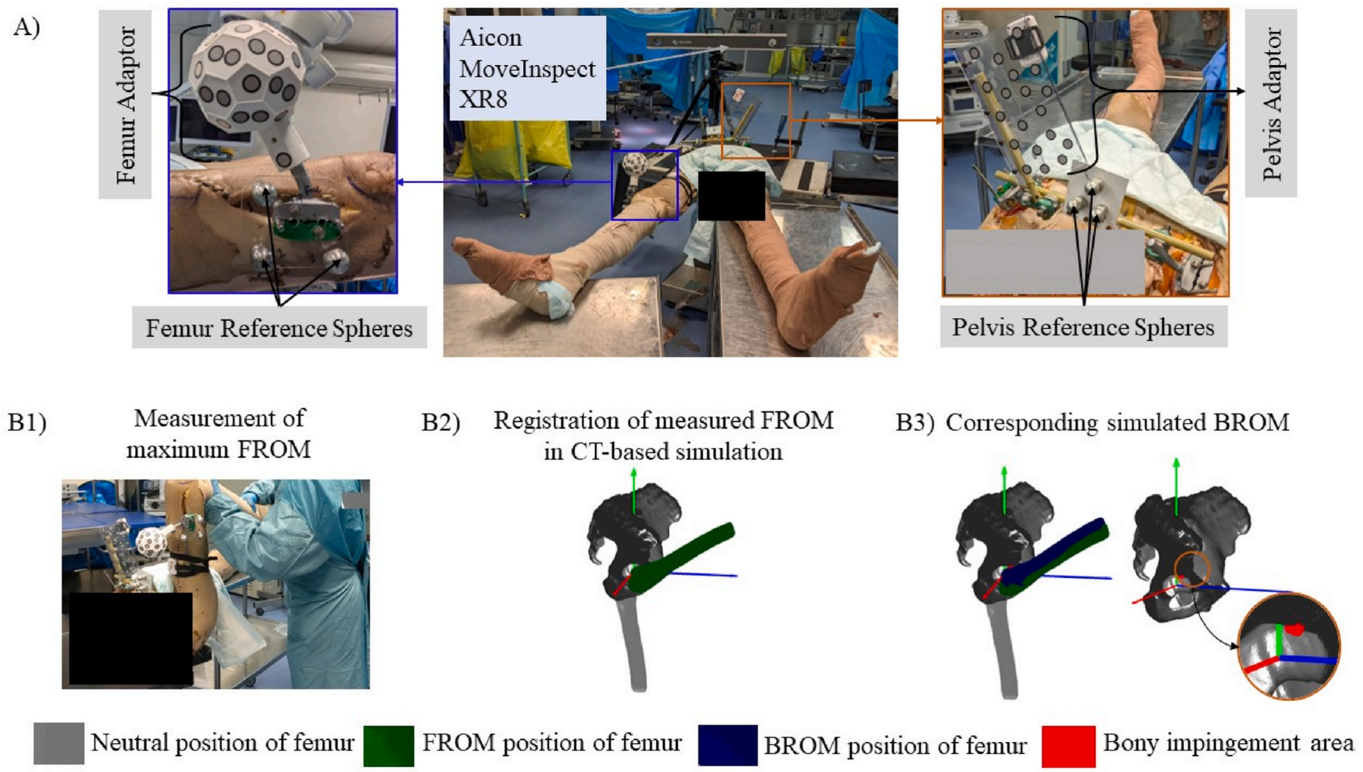


**Fig. 1.** Experimental set-up, registration, and simulation workflow of the study. (A) Pelvis adaptor and pelvis reference spheres are attached to the pelvis. Similarly, femur adaptor and femur reference spheres are affixed to the femur. (B1) a representative maximum FROM measurement position, (B2) registration and recreation of the experimental FROM position in CT-scan based in-house hip motion simulation, (B3) calculation of corresponding simulated BROM position.

experienced orthopaedic surgeons (Author 8 and Author 5) to define the maximum passive FROM (Fig. 1B1). The following pure joint motions were performed: (a) maximum flexion, (b) maximum extension, (c) maximum abduction. In addition, the following combined motions were performed to cover all the possible maximum or limiting hip positions: (1) Flexion-IR to measure the maximum internal rotation (IR) throughout the flexion range with three different levels of abduction/adduction, (b) Extension-ER to measure the maximum external rotation (ER) throughout the extension range with three different levels of abduction/adduction, (3) Flexion-ER to measure maximum ER with different combinations of flexion and abduction/adduction; (4) Extension-IR to measure maximum IR with different combinations of extension and abduction/adduction. In the Flexion-IR movements, the flexion range encompassed from 0° to the maximum flexion point, progressing in roughly 10° step-size increments, as judged clinically by the surgeon. Similarly, Extension-ER covered extension from 0° to its maximum, also increasing in roughly 10° intervals. The step size of 10° was an approximate value and clinically determined during the experiment. It served as a target for the surgeons to perform a broad range of movements with reasonable consistency. Three levels of abduction/adduction, used in Flexion-IR and Extension-ER, were defined as follows: (i) 'neutral', where abduction/adduction was less than 10°, (ii) 'lower', where the abduction/adduction was 10°–20°; (iii) 'higher', where abduction/adduction was greater than 20°. An extensive set of these passive maximum FROM measurements was performed, comprising at least 90 positions for each of the nine hip cases (Table 1). Each manoeuvre was held for 5 s in the maximum position, during which measurements were taken. All these maximum manoeuvres were repeated three times for measurement consistency, considered as a measurement 'run' in this paper.

**Table 1**
List of the passive maximum FROM positions that were measured during each hip experiment.

| FROM Positions | Flex-Extn component | Abd-Add component | Rotation component |
|---|---|---|---|
| **Pure Flex** | Max Flex | <5° | <5° |
| **Pure Extn** | Max Extn | <5° | <5° |
| **Pure Abd** | <5° | Max Abd | <5° |
| **Flex-IR**(30 to 50 maximum FROM positions) | 0° to Max Flex with step size of 10° i.e., 0°, 10°, 20°, …, Max Flex | neutral Abd/Add | Max IR |
| | | lower Abd | Max IR |
| | | higher Abd | Max IR |
| | | lower Add | Max IR |
| | | higher Add | Max IR |
| **Extn-ER**(15 to 25 maximum FROM positions) | 0° to Max Extn with step size of 10° i.e., 0°, 10°, 20°, …, Max Extn | neutral Abd/Add | Max ER |
| | | lower Abd | Max ER |
| | | higher Abd | Max ER |
| | | lower Add | Max ER |
| | | higher Add | Max ER |
| **Flex-ER**(30 to 50 maximum FROM positions) | 0° to Max Flex with step size of 10° i.e., 0°, 10°, 20°, …, Max Flex | neutral Abd/Add | Max ER |
| | | lower Abd | Max ER |
| | | higher Abd | Max ER |
| | | lower Add | Max ER |
| | | higher Add | Max ER |
| **Extn-IR**(15 to 25 maximum FROM positions) | 0° to Max Extn with step size of 10° i.e., 0°, 10°, 20°, …, Max Extn | neutral Abd/Add | Max IR |
| | | lower Abd | Max IR |
| | | higher Abd | Max IR |
| | | lower Add | Max IR |
| | | higher Add | Max IR |

neutral Abd/Add: <10°; lower Abd/Add: 10°–20°; higher Abd/Add: >20°.

### 2.3. Hip BROM simulation

3D geometries of pelvis and femur were created from post-experiment CT images (GE medical systems revolution, 120 kV, 1.25 mm slice thickness, 0.98 mm × 0.98 mm x 1.25 mm voxel size) along with the identification of bony landmarks using Simpleware™ ScanIP software (Version 2022, Synopsys Inc., Mountain View, USA). The Pelvic Coordinate System (PCS) and Femoral Coordinate System (FCS) were then constructed using the four pelvic and three femoral landmarks respectively according to the ISB recommendation [27]. The neutral position of the femur and pelvis was defined by aligning the PCS and FCS with World Coordinate System (WCS), with the hip joint centre coinciding with the origin of the WCS [10]. The hip motions were then simulated using an in-house Matlab (Version 2021b, The MathWorks Inc, Natick, Massachusetts, USA) programme, and subsequently, bony impingement (BI) was identified where the pelvis and femur intersected [3,10,26]. The BROM envelope was defined as the boundary within which all hip positions did not result in BI. The detailed description of the developed method was described by Palit et al. [26].

### 2.4. Calculate relation between measured cadaveric FROM and simulated BROM

The centre points of pelvis and femur reference spheres were determined using the measurement data from both the AICON system and post-CT scan segmentation. These centre points were then used to register the directly measured cadaveric movements with the CT-based hip model [26]. Subsequently, 3D positions and orientation of the femur relative to the pelvis were recreated computationally for each measured maximum FROM position (Fig. 1B2). The FROM position was then decomposed into three independent angular motions of following order: flexion/extension, abduction/adduction and internal/external rotation. Among these, one motion component acted as the variable/leading component which was then systematically increased by 0.5° step size while keeping the other two decomposed secondary angular motions constant (Table 1) [26]. This process continued until BI was detected which provided the corresponding simulated BROM (Fig. 1 B3). The relationship between the experimental FROM and simulated BROM was classified as follows: (a) closely related (mean difference <5°), (b) moderately related (5° < mean difference <15°), and (c) weakly related (mean difference >15°). A close relationship implied that the soft tissues had a minimal role in limiting the ROM. The FROM and corresponding BROM was presented as mean ± SD for 9 hip cases. The association between FROM and BROM was assessed with paired sample *t*-test and Pearson correlation coefficient. All the analyses were performed in Matlab. Significance was set at $p < 0.05$.

## 3. Results

### 3.1. FROM vs BROM for pure joint motion

Fig. 2 illustrates the measured maximum FROM, corresponding simulated BROM, and their differences for flexion, extension, and abduction. The mean ± SD values for experimental FROM were 108.4° ± 10.1° for flexion, 20.5° ± 10.2° for extension, and 33.5° ± 5.6° for abduction (Table 2). The corresponding computed BROM values were as follows: flexion = 111.4° ± 11.5°; extension = 72.3° ± 19.1°; and abduction = 52.1° ± 10.2° (Table 2).

For hip flexion, it was observed that the difference between FROM and corresponding BROM was always less than 10° for all cases, and less than 5° for 6 cases out of 9 cases. Notably, FROM and BROM were identical across all runs for two cases (cases 4 and 6), and in few runs for hip cases 2, 3, 5, and 9 (Fig. 2 A1 and A2). This suggests that BI during hip flexion had occurred. In contrast, the differences between FROM and BROM for extension were always greater than 35° (Fig. 2B1 and B2). The difference between measured and calculated abduction was less than 20° for 7 cases whereas the remaining 2 cases displayed larger differences of more than 30° (Fig. 2C1 and C2). The average differences between FROM and BROM were as follows: flexion: 3.1° ± 3.9°; extension: 51.9° ± 14.4°; and abduction, 18.6° ± 11.3° (Table 2). Therefore, flexion showed a close relationship between FROM and BROM (mean difference <5°) whereas extension and abduction demonstrated a weak relationship (mean difference >15°).

### 3.2. FROM vs BROM: hip joint rotation

Figs. 3 and 4 illustrate the minimum and maximum differences observed in all movement runs in all hips between measured FROM and

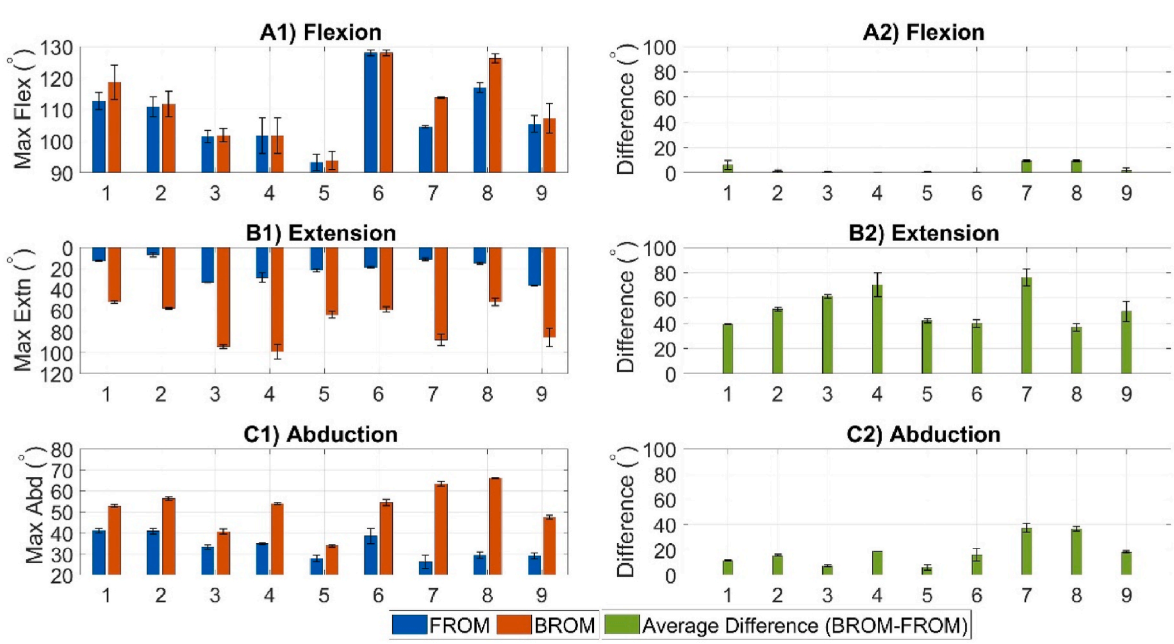


**Fig. 2.** Experimentally measured FROM (A1, B1, C1), corresponding simulated BROM (A1, B1, C1) and their differences (A2, B2, C2) for flexion, extension, and abduction for each of the 9 hip cases.

**Table 2**
Summary of experimental FROM for pure hip motion (flexion, extension, and abduction) and maximal IR (Flex-IR and Extn-IR), corresponding simulated BROM, differences between FROM and BROM, p-value from paired *t*-test, and Pearson coefficient. Orange and green colour represent weak and strong relationships respectively between FROM and BROM.

| Maximum FROM Positions | | | FROM (°) | BROM (°) | Difference (°) | *P* value | Pearson Coefficient |
|---|---|---|---|---|---|---|---|
| Pure Flexion | | | 108.4±10.1 | 111.4±11.5 | 3.1±3.9 | 0.046 | 0.94 |
| Pure Extension | | | 20.5±10.2 | 72.3±19.1 | 51.9±14.4 | 0.000 | 0.66 |
| Pure Abduction | | | 33.5±5.6 | 52.1±10.2 | 18.6±11.3 | 0.001 | 0.07 |
| Max IR | Flex >70° | Neutral Abd/Add | 17.4±8.9 | 20.4±10.6 | 2.9±4.5 | 0.085 | 0.95 |
| | | lower Abd | 20.3±8.5 | 24.5±7.6 | 4.7±4.8 | 0.023 | 0.72 |
| | | higher Abd | 24.9±8.0 | 29.9±7.4 | 4.9±3.6 | 0.039 | 0.89 |
| | | lower Add | 10.2±3.2 | 13.9±5.8 | 3.7±4.2 | 0.060 | 0.70 |
| | | higher Add | 15.1±1.9 | 19.2±7.0 | 4.9±4.6 | 0.112 | 0.30 |
| | Flex <70° | Neutral Abd/Add | 31.4±5.5 | 74.2±14.5 | 42.8±10.2 | 0.000 | 0.85 |
| | | lower Abd | 32.6±4.3 | 66.5±18.4 | 33.8±15.1 | 0.000 | 0.82 |
| | | higher Abd | 29.4±7.6 | 51.9±16.2 | 22.5±15.8 | 0.009 | 0.27 |
| | | lower Add | 28.1±4.5 | 70.5±18.5 | 42.5±18.8 | 0.000 | 0.08 |
| | | higher Add | 23.8±6.3 | 43.5±6.5 | 20.5±10.3 | 0.004 | -0.26 |
| | Extn | Neutral Abd/Add | 25.1±4.1 | 104.8±7.5 | 79.7±4.6 | 0.000 | 0.84 |
| | | lower Abd | 22.8±7.7 | 98.8±9.1 | 76.0±1.4 | - | - |
| | | lower Add | 21.2±6.9 | 99.1±10.6 | 77.8±13.1 | - | - |

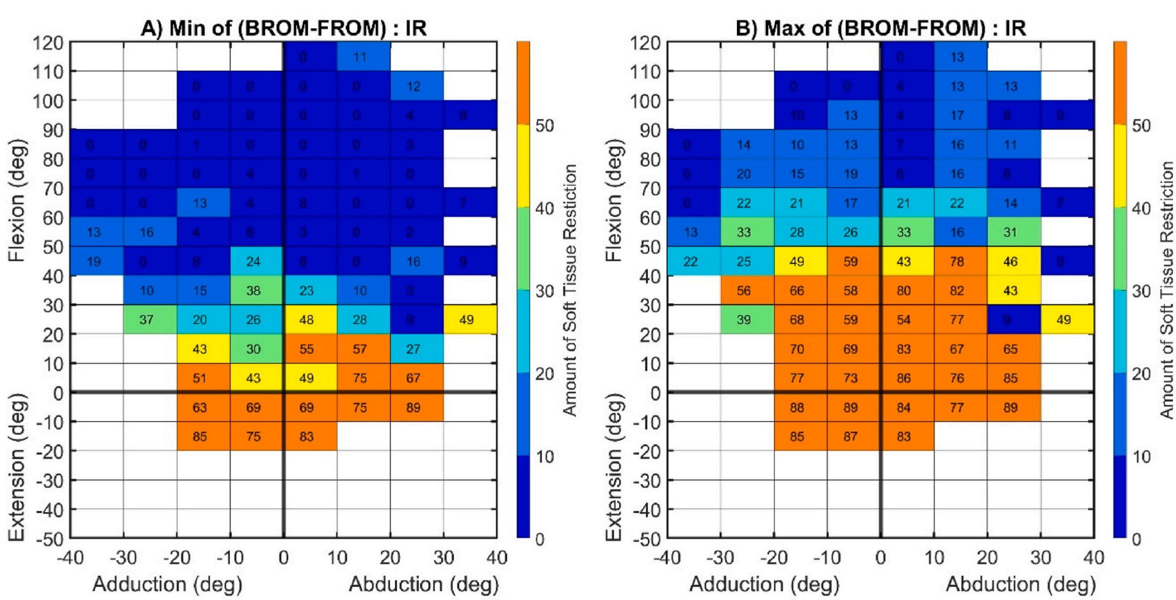


**Fig. 3.** The differences in experimental FROM and corresponding simulated BROM for maximum IRs in Flex-IR and Extn-IR motions with various degrees of abduction and adduction across 9 hip cases. The positive and negative y-axis depict flexion and extension respectively whereas the positive and negative x-axis define abduction and adduction respectively. The colourmap displays intervals in increments of 10°, while the text within each box provides exact numerical differences. The topmost orange colour in colour bar represented any values more than 50°. (A) Minimum and (B) Maximum of the differences between measured and simulated maximum IRs.

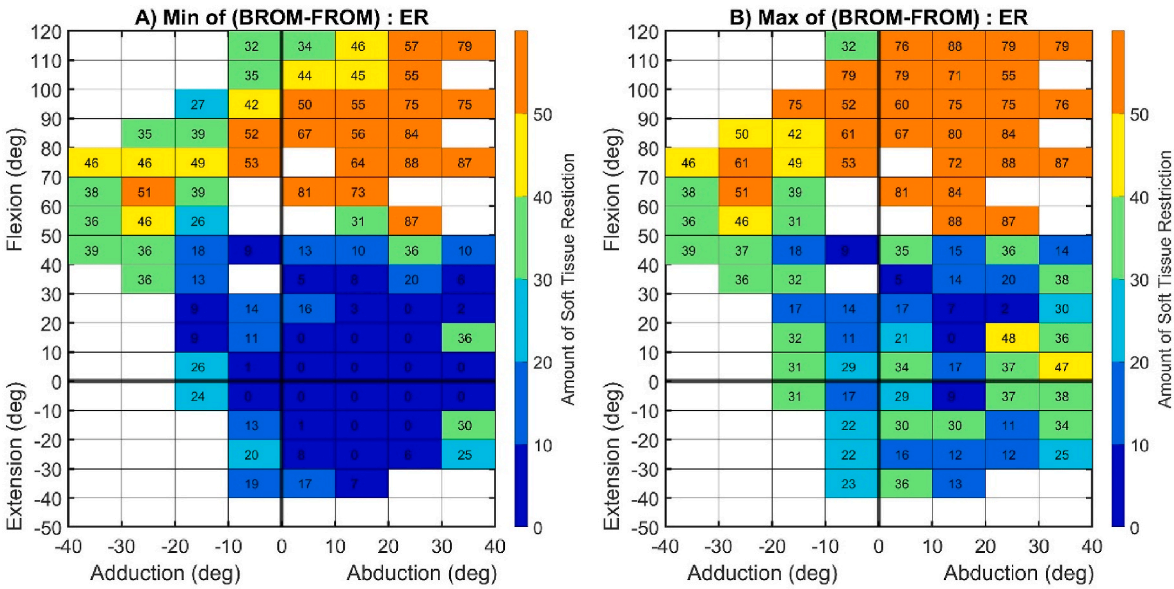


**Fig. 4.** The differences in experimental FROM and corresponding simulated BROM for maximum ERs in Flex-ER and Extn-ER motions with various degrees of abductions and adductions across all 9 hip cases. The positive and negative y-axis depict flexion and extension respectively whereas the positive and negative x-axis define abduction and adduction respectively. The colourmap displays intervals in increments of 10°, while the text within each box provides exact numerical differences. The topmost orange colour in colour bar represented any values more than 50°. (A) Minimum and (B) Maximum of the differences between measured and simulated maximum ERs.

**Table 3**
Summary for experimental FROM for maximum ER cases (Extn-ER and Flex-ER), corresponding simulated BROM, differences between FROM and BROM, p-value from paired *t*-test, and Pearson coefficient between FROM and BROM across 9 hip cases to highlight the amount of soft tissue restriction for pure joint motions, Flex-IR and Extn-ER combined motions. Orange and yellow colour represented weak and moderate relationships respectively between measured FROM and simulated BROM.

| Maximum FROM Positions | | | FROM (°) | BROM (°) | Difference (°) | *P* value | Pearson Coefficient |
|---|---|---|---|---|---|---|---|
| Max ER | Extn <20° | Neutral Abd/Add | 23.3±9.7 | 35.2±9.2 | 12.1±7.3 | 0.002 | 0.71 |
| | | lower Abd | 27.9±15.6 | 35.4±11.4 | 7.4±8.2 | 0.054 | 0.86 |
| | | higher Abd | 32.1±13.6 | 42.4±13.2 | 10.3±8.7 | 0.007 | 0.78 |
| | Extn >20° | Neutral Abd/Add | 13.6±7.7 | 35.1±3.1 | 22.1±10.9 | - | - |
| | | lower Abd | 28.9±1.3 | 37.1±4.4 | 8.2±3.4 | - | - |
| | | higher Abd | 24.1±10.5 | 38.5±6.5 | 15.1±9.5 | - | - |
| | Flex <30° | Neutral Abd/Add | 29.1±11.2 | 42.1±11.9 | 12.9±7.5 | 0.004 | 0.78 |
| | | lower Abd | 42.4±8.1 | 48.1±7.9 | 5.8±4.7 | 0.044 | 0.83 |
| | | higher Abd | 40.8±18.5 | 55.4±10.8 | 14.5±15.6 | 0.021 | 0.57 |
| | Flex >30° | Neutral Abd/Add | 34.4±13.5 | 77.0±27.1 | 42.6±20.1 | 0.000 | 0.65 |
| | | lower Abd | 44.7±12.7 | 104.5±9.9 | 59.8±11.5 | 0.000 | 0.51 |
| | | higher Abd | 43.8±9.8 | 102.2±21.4 | 58.6±19.4 | 0.000 | 0.42 |
| | | lower Add | 36.9±19.4 | 65.4±27.2 | 28.9±18.1 | 0.003 | 0.75 |
| | | higher Add | 33.6±5.7 | 73.5±7.9 | 39.9±8.9 | 0.002 | 0.17 |

simulated BROM for maximal IR and ER respectively. Tables 2 and 3 summarise the statistics of the differences. Appendix A details the FROM measurement results for maximal IRs and ERs.

It was observed that the differences in Flex-IR across various abduction/adduction combinations remained remarkably consistent and below 20°, particularly for flexion values exceeding 70° (Fig. 3 and Table 2). In addition, the Pearson coefficient was more than 70 % for majority of the deep flexion (>70°), although not all p-values were >0.05, indicating that significant differences may exist (Table 2). Overall, the difference for maximum IR at deep flexion (>70°) was 4.3° ± 4.6°, indicating close relationship between FROM and BROM.

There was a moderate relationship between FROM and BROM for maximal ER when the hip was in a small amount of flexion (<30°) or extension (<20°) (Table 3 and Fig. 4). The overall differences in maximal ER were 10.3° ± 5.8° when flexion was 0-30°, and 11.7° ± 7.2° when extension was 0-20°.

In contrast, the differences between FROM and BROM were significantly greater for IR motions where flexion was <70° (Table 2 and Fig. 3) or in any extension (Table 2 and Fig. 3). The difference was consistently greater than 60° and approaching 90° in some cases. The difference was also substantial for Flex-ER combined motions when flexion was higher than 30° (Table 3 and Fig. 4). Similarly, the Extn-ER with high extension (>20°) showed large difference between FROM and BROM (Table 3 and Fig. 4).

Overall, the weak relationship results were summarised as follows: (i) maximum extension (51.9° ± 14.4°), (ii) maximum abduction (18.6° ± 11.3°), (iii) maximum IR at lower flexion (<70°) (37.1° ± 9.4°), (iv) any Extn-IR combined motions (79.6° ± 4.8°) (v) Flex-ER combined motions when flexion was higher than 30° (45.9° ± 11.3°) (vi) Extn-ER combinations at high extension angles (>20°) (15.8° ± 4.8°).

In certain instances, the difference between FROM and BROM was observed to be 0° as evident from Figs. 2, 3A and 4A. This observation suggested the presence of a BI during healthy hip motions such maximum flexion, maximum IR at deep flexion, maximum ER at low flexion and low extension. The details of the occurrence of BI are included in Appendix B.

## 4. Discussion

Dynamic 3d pre-operative planning of THA involves moving the planned hip into various positions to check for adverse biomechanics such as impingement or edge loading. It is important to only simulate movements that are functionally relevant for the individual patient. It is possible to determine the theoretical BROM of the normal hip from CT, but this is only useful if the relationship of this BROM to the FROM is known. In this paper, an experimental study was conducted on nine normal cadaveric hips to measure the passive maximum FROM, and subsequently register it onto a CT-based hip motion simulation to investigate the relationship between FROM and simulated BROM. An extensive set of FROM measurements was performed, comprising at least 90 maximum positions for each of the nine hip cases, to provide a thorough representation of the majority of clinically relevant hip motions. The study finding are as follows:

(a) The simulated BROMs which are most clinically relevant due to their close correspondence with the FROM are: (i) maximal flexion, (ii) maximal IR in deep flexion (>70°) (Flex-IR). Therefore, the calculated BROM values for these hip movements can be used in dynamic 3D planning simulations of THA.
(b) Maximal ER in minimal flexion-extension (flexion <30° and extension <20°) had moderate relationship between FROM and FROM, and therefore, could potentially also be used in clinical simulation to represent FROMs.
(c) It was observed that soft tissue and ligaments play a dominant role for the following movements: (i) maximum extension, (ii) maximum abduction, (iii) maximum IR with lower flexion (<70°), (iv) any Extn-IR motions, (v) Flex-ER with higher flexion (>30°), and (vi) Extn-ER with higher extension angles (>20°). Therefore, BROM would not be a good representation for these FROM positions, and therefore, not suitable for dynamic 3D planning simulations of THA.
(d) Finally, it was found that BI between the femur and pelvis can occur in healthy normal hips particular during: (i) maximum flexion, (ii) maximum IRs at deep flexion (>70°), (iii) maximum [26].

It was observed that the experimental maximum FROM was well within the range of previously reported measurement of normal hip motions [25,28]. Close agreement was observed, especially for the following manoeuvres: maximum flexion, extension, abduction, IR at 90° Flexion and max ER at 20° (Table 2). The computed BROM values were also consistent with the previous simulation studies of normal hips [10,29–32]. For example, the simulated BROM values for flexion, extension, and abduction were found to be 111.4° ± 11.5°, 72.3° ± 19.1°, and 52.1° ± 10.2°, respectively. These values align closely with previously reported findings of flexion (122.5° ± 11.1°) [32,33], extension (58.0° ± 20.4°) [33] or (61.3° ± 32.0°) [31], and abduction (61.0° ± 14.0°) [31,33]. However, one notable difference in this study was that the computed flexion, extension, abduction values were not purely isolated joint motions as the hips were moved manually. Therefore, while calculating the corresponding BROM to a limiting FROM, there were minor contributions of other motions that were introduced during the FROM measurements. For example, the flexion value was always associated with some amount of abduction/adduction and internal rotation/external rotation in this study.

The mean differences of <5° and 5°-15° (section *Comparison between measured FROM and simulated BROM* under 'Materials and Methods') were used to define the close and moderate relation respectively as these ranges of variation in ROM were considered clinically relevant. Although Pearson coefficient exceeded 70 % for majority of the close and moderate relations, inconsistent p-values suggested that statistically significant differences might persist between BROM and FROM (Tables 2 and 3). The p-values and Pearson Coefficient are not included in Tables 2 and 3 when the data point was less than 5. The differences between the FROM and BROM values for max IR at 90° flexion with neutral abduction/adduction were 3.1° ± 4.2°, which closely agreed with previously reported values of 4.9° ± 3.8° [25]. Hence, these representative BROMs could serve as subject specific FROMs. However, movements which demonstrated weak relationships between BROM and FROM should not be used in simulation. Also, the presence of BI during limiting FROM positions was in line with previous findings.

The study had few limitations that need to be acknowledged. Firstly, the average age of the cadaveric specimens in this study was in the range of 70–79 years. Typically, soft tissues tend to become stiffer in older individuals, and it is possible that the measurement results could have varied had younger donors been used. Also, cadaveric soft tissues and ligaments are generally stiffer and impose greater constraints on joint motion than those in living patients due to the absence of blood flow, altered hydration, and preservation techniques like freezing or embalming. A recent study by Hananouchi et al. [34] found that cadaver and in-vivo hip labrum tissue was of similar stiffness, but the in-vivo measures were still less stiff than the intact cadaver tissue. Consequently, the restraining effect of soft tissue and ligaments on hip FROM is likely to be lower in live patients compared to cadaver studies, meaning the measured FROM would more closely align with the simulated BROM. Therefore, the study's conclusion (i.e., BROM for pure flexion, internal rotation in deep flexion, and external rotation in neutral extension closely represents actual FROM) would remain valid. Secondly, the determination of the maximum FROM was dependent on the evaluation of an experienced surgeon rather than employing a robot or a force-based impingement detection system. This choice was made due to the perceived reliability of the surgeon's 25 years of experience in accurately identifying the limiting motion, compared to utilising a robot, where the value of the limiting force remained uncertain. Finally, it's important to note that the study did not incorporate the translation of the femoral head within the acetabulum during virtual hip motion in the simulation. Further research is needed to determine how such patient specific BROM simulations can be applied to patients with hip arthritis, who often have abnormal bony anatomy (particularly osteophytes) and soft tissue contractures.

In summary, a comprehensive set of passive maximum FROM measurements was performed including pure hip joint motions (Flexion, Extension, Abduction) and various combined motions involving Flexion-IR, Flexion-ER, Extension-ER and Extension-IR with various degrees of abduction/adduction for each of the nine hip cases. The measured FROM was compared with a CT-based simulated BROM. It was observed that soft tissue and ligaments had varying degrees of influence on different FROM positions. Maximum flexion and Flex-IR at deep flexion

(>70°) exhibited close relation between FROM and BROM, while maximum ER with minimal flexion-extension represented a moderate relation. Indeed, bony impingement was observed during these motions for a few hip cases. Therefore, in theory, subject specific BROM values for these positions could be computed for patients with arthritis using CT images of their contralateral hip or (where it was normal) or from the historical imaging (before the onset of significant arthritis). This would facilitate the practical and reliable utilisation of the personalised simulated BROMs as a valuable target FROM for pre-operative hip replacement planning of the arthritic side.

## CRediT authorship contribution statement

**Arnab Palit:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mark A. Williams:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Ercihan Kiraci:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Vineet Seemala:** Writing – review & editing, Methodology, Investigation, Data curation. **Vatsal Gupta:** Writing – review & editing, Methodology, Investigation, Data curation. **Jim Pierrepont:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Christopher Plaskos:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Richard King:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. However, the study received funding from Corin Group, UK (AP) and HVM Catapult, UK (AP and EK). VS receives PhD studentship from University of Warwick. MAW is a Professor at University of Warwick. JP and CP are employee of Corin. RK receive royalties and consultancy fees from Brainlab, and payments from Corin for consultancy and education.

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## Appendix A

*Experimental FROM: Max IR and Max ER*

Figure A1 shows all the measured passive maximum FROM positions, at least 90 positions for each case through (a) maximum flexion, (b) maximum extension, (c) maximum abduction, (d) Flexion-IR to measure the maximum internal rotation (IR) throughout the flexion range with three different levels of abduction/adduction, (e) Extension-ER to measure the maximum external rotation (ER) throughout the extension range with three different levels of abduction/adduction, (f) Flexion-ER to measure maximum ER with different combinations of flexion and abduction/adduction; (g) Extension-IR to measure maximum IR with different combinations of extension and abduction/adduction.

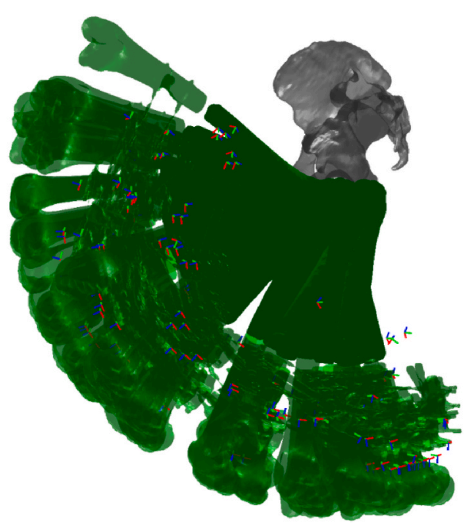

**Fig. A1.** A representative all the measured passive maximum FROM positions.

Figures A2 and A3 display the average values and corresponding variation of experimentally measured max IRs and ERs respectively across the nine different hip cases involving various combinations of flexion/extension and abduction/adduction. The positive and negative y-axis of these plots depicted flexion and extension respectively whereas the positive and negative x-axis defined abduction and adduction respectively. The colourmap represents the range of maximum ROMs, with specific values enclosed within each box. For example, the green colour boxes represent 30°–40° range of maximum IRs in Fig. 3A. However, the green coloured boxes also included the actual maximum IRs such as 31°, 36° etc.

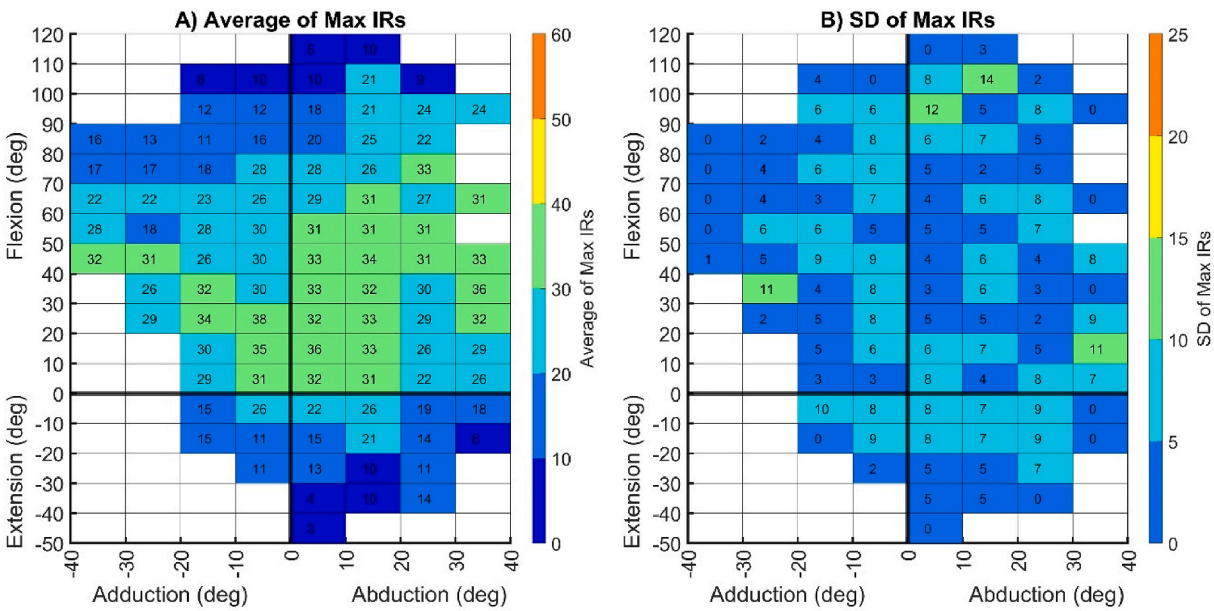


**Fig. A2.** (A) Average and (B) standard deviation (SD) of experimentally measured max IRs across nine different cases involving various combinations of flexion/extension and abduction/adduction. 0° SD indicates the limitation of the data points within the category. The colourmap displays intervals in increments of (A) 10° and (B) 5°. The text within each box provides precise numerical values.

It was observed that the maximum IRs consistently remained below 40° when flexion ranged from 0° to 70° (particularly within the 20°–40° range), regardless of abduction and adduction values (Fig A2 A). However, during deep flexion (>70°), the average maximum IR dropped below 30°, except when the hip was highly abducted. On the other hand, the measured maximum IRs for extension and various abduction/adduction ranges consistently remained below 30°, and they decreased to below 15° when extension exceeded 10° (Fig A2 A). The standard deviation (SD) plots demonstrated minimal variation among the different hip cases, with 0° variation indicating that only a single datapoint was captured in this position (Fig A2 B).

The average maximum ERs during extension consistently fell within the 10°–40° range (Fig A3 A). Variations in maximum ERs were below 25° when extension values were below 20° (0° to −20° extension in Fig A3 B), while the variation remained consistently below 5°, when extension exceeded 20° (−20° to −30° extension in Fig. 4B). On the other hand, the observed average maximum ERs for various combinations of flexion and abduction consistently exceeded 30° (with a few exception) and increased to over 40° when flexion surpassed 20° (Fig A3 A). The corresponding variation in experimentally measured max ERs were higher in comparison with the variations observed for IRs measurements, and sometimes it was more than 20° (Fig A3 b) with 0° variation indicating that only a single datapoint was captured in this position.

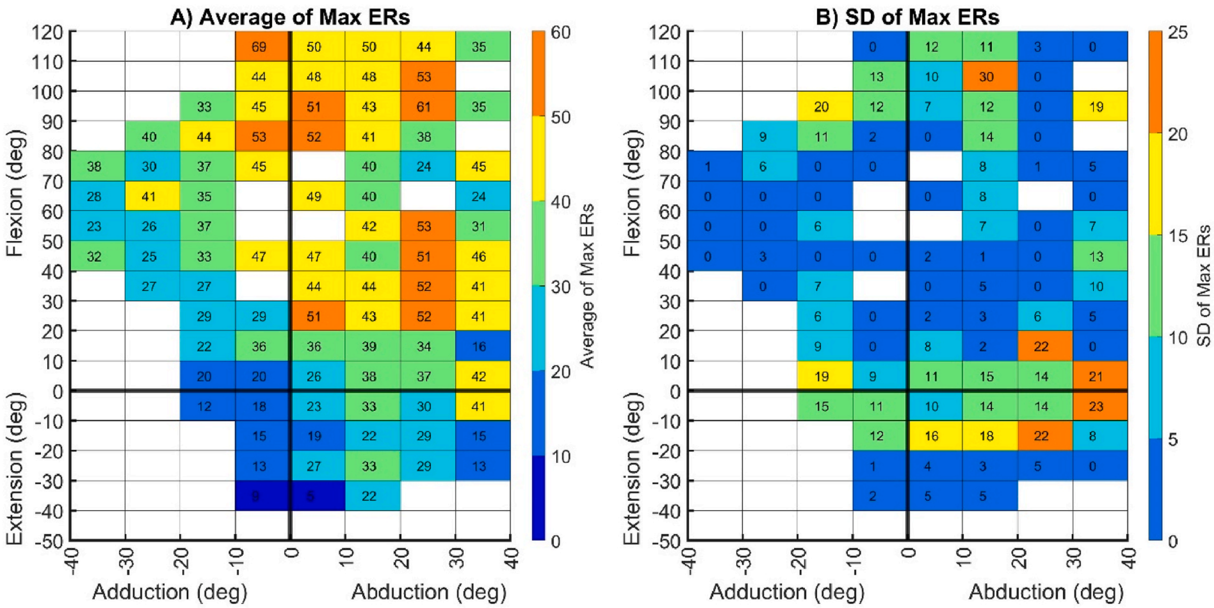


**Fig. A3.** (A) Average and (B) standard deviation (SD) of experimentally measured max ERs across nine different cases involving various combinations of flexion/extension and abduction/adduction. 0° SD indicates the limitation of the data points within the category. The colourmap displays intervals in increments of (A) 10° and (B) 5°. The text within each box provides precise numerical values.

## Appendix B

Figure B1 summarises the occurrence of BI across all 9 cases, with the number within each grid representing the rate of occurrence of BI considering all the experimental measurement runs across 9 hip cases. For example, there was 45 % rate of occurrence of BI for maximum IR values with deep flexion 90°–120° and abduction values of 10°–20°, across 9 hip cases. It was observed that BI was present for some hip cases for maximum IR motions with deep flexion (flex>60°). The rate of occurrence was always more than 45 % when flexion was more than 90°. There was no sign of BI for any Flex-IR movements when flexion was less than 30°, and majority of the cases with flexion values ranging 30°–60°. BI was also observed for Flex-ER movement with low flexion (<30°) with abducted hip. Interestingly, few BI was also found for Extn-ER manoeuvres with various abductions and with slight adduction (<10°).

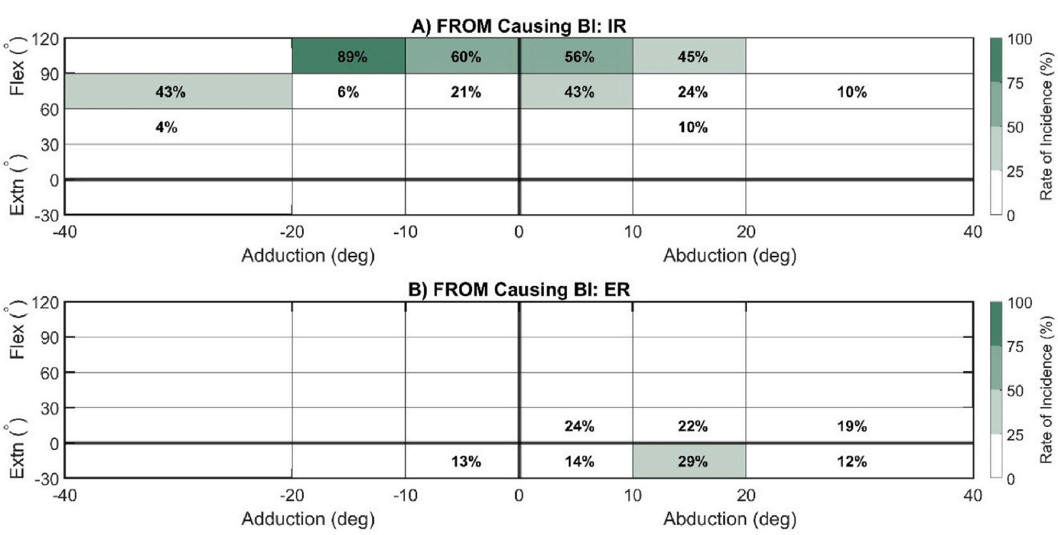


**Fig. B1.** Representation of FROMs that lead to bony impingement (BI) for (A) max IR and (B) max ER motions. The numbers within each grid indicate the rate of occurrence for all measurement runs across 9 hip cases.

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