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RESEARCH ARTICLE

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The effect of surgical change to hip geometry on hip biomechanics after primary total hip arthroplasty

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Abstract

The aim of this study was to determine the effect of surgical change to the acetabular offset and femoral offset on the abductor muscle and hip contact forces after primary total hip arthroplasty (THA) using computational methods. Thirty-five patients undergoing primary THA were recruited. Patients underwent a computed tomography scan of their pelvis and hip, and underwent gait analysis pre- and 6-months postoperatively. Surgically induced changes in acetabular and femoral offset were used to inform a musculoskeletal model to estimated abductor muscle and hip joint contact forces. Two experiments were performed: (1) influence of changes in hip geometry on hip biomechanics with preoperative kinematics; and (2) influence of changes in hip geometry on hip biomechanics with postoperative kinematics. Superior and medial placement of the hip centre of rotation during THA was most influential in reducing hip contact forces, predicting 63% of the variance ($p < 0.001$). When comparing the preoperative geometry and kinematics model, with postoperative geometry and kinematics, hip contact forces increased after surgery (0.68 BW, $p = 0.001$). Increasing the abductor lever arm reduced abductor muscle force by 28% ($p < 0.001$) and resultant hip contact force by 17% (0.6 BW, $p = 0.003$), with both preoperative and postoperative kinematics. Failure to increase abductor lever arm increased resultant hip contact force 11% (0.33 BW, $p < 0.001$). In conclusion, increasing the abductor lever arm provides a substantial biomechanical benefit to reduce hip abductor and resultant hip joint contact forces. The magnitude of this effect is equivalent to the average increase in hip contact force seen with improved gait from pre-to post-surgery.

KEYWORDS

hip biomechanics, hip geometry, musculoskeletal model, simulation

1 | INTRODUCTION

Implant positioning during total hip arthroplasty (THA) is important to improve postoperative pain and patient function,[1–4] reduce the risk of impingement,[5] dislocation,[6] and excessive wear,[7,8] and lower revision rates.[9] The link between implant positioning and poor patient-reported and clinical outcomes is typically discussed in light of the effect of implant positioning on hip contact forces, which may increase when hip geometry is not restored through THA. Indeed, restoring the normal anatomy of the hip joint through THA provides a mechanical advantage to the hip abductor muscles,[10] which in turn may decrease abductor muscle and hip joint contact forces during gait.[11]

During gait, the hip abductor muscles support the upper body's mass and control the pelvis.[12] The abductor muscles are mechanically disadvantaged because the distance between the centre of the femoral head and the muscle line of action is markedly smaller than the distance between the centre of the femoral head and the body's axis (acetabular offset).[12] Accordingly, several authors emphasize the importance of medialising the cup during THA to reduce the distance between the body's' axis and centre of the femoral head,[10,13–15] and compensate with an equivalent increase in femoral offset to achieve a biomechanical benefit.

Modern-day materials and manufacturing processes, combined with navigation and robotics technology, has resulted in many surgeons moving away from the traditional philosophy defined more than half a century ago of medialising the cup to achieve initial fixation.[16–18] These surgeons typically aim to restore the native centre of rotation and femoral offset, while preserving acetabulum bone stock. However, the consequence is that patients may not benefit from the biomechanical advantage of medialising the cup, which can have a significant effect of abductor muscle and joint contact forces.

Previous biomechanical studies using elusive mathematical models have focussed on femoral offset and overlooked acetabulum offset, and never considered patient-specific kinematics and muscle-moment arms to substantiate the effect of cup medialization on muscle and hip joint contact forces.[4,11,19,20] A dynamic simulation framework provides an opportunity to isolate the effect of hip joint geometry on abductor muscle and joint contact forces, and consider the influence of subject-specific gait kinematics on muscle and joint contact forces. Therefore, this study addresses the following question: do surgical changes in hip joint geometry following primary THA, specifically acetabular and femoral offset, result in significant changes in hip abductor muscle forces and hip contract forces?

2 | METHODS

Level of evidence: Level 3.

Hip joint geometry and kinematics both influence muscle and hip joint contact forces. Therefore, this study determined the effect of surgical change by THA to the centre of rotation (COR) and femoral offset together with, and independent of, gait function on hip contact forces. To this end, the following thought experiments were performed in silico:

1) A preoperative estimate of hip contact forces was established using preoperative motion capture data and preoperative hip joint geometry (Figure 1A). Hip joint geometry in this experiment refers to the specification of COR in the three orthogonal directions, and femoral offset. Subsequently, to isolate the effect of hip joint geometry, we modeled what the effect on hip contact forces would be if the patient continued to walk with the same kinematics post-surgery but the internal geometry was surgically adjusted (Figure 1A).
2) A postoperative estimate of hip contact forces was established using 6-months postoperative gait kinematics and postoperative hip joint geometry. Subsequently, we modeled what the effect would be if we took the patient's postoperative kinematics, but we applied them to a model with preoperative internal geometry, that is, if the surgeon did not adjust the COR or femoral offset (Figure 1B).

2.1 | Participants

Patients scheduled to undergo primary THA between August 2016 and February 2018 at a large metropolitan public hospital were recruited. Medical images of the pelvis and hips were obtained from computed tomography (CT) and gait analysis was performed both before and 6-months after THA. Patients were eligible for recruitment if their primary reason for THA was hip OA, avascular necrosis of the femoral head, or inflammatory arthritis. Exclusion criteria included a neurological/neuro-degenerative condition affecting walking gait or motor control, pregnancy during time of testing, revision of a primary THA, or an inability to understand written and spoken English. All THAs were performed through a posterior approach and all patients received the same implant design: a press-fit Trilogy acetabular shell and a cemented CPT femoral stem (Zimmer Biomet, Warsaw, Indiana). The study protocol was approved by our local Human Research Ethics Committee (REF: R20160807). All participants provided written informed consent before participating in any research.

2.2 | CT scan acquisition and determination of the centre of rotation locations and the abductor lever arm

The CT images of the full pelves and femora were acquired with each participant in a supine position, with feet slightly internally rotated position, pre-and postoperatively. Scans were acquired using a dual-energy Siemens SOMATOM Definition Flash (Siemens, Erlangen, Germany). Each participant's centre of rotation was determined from 3-dimensional reconstructions generated by segmenting the CT images using a semi-automatic threshold-based approach in the ScanIP module (version 5.0, Simpleware).

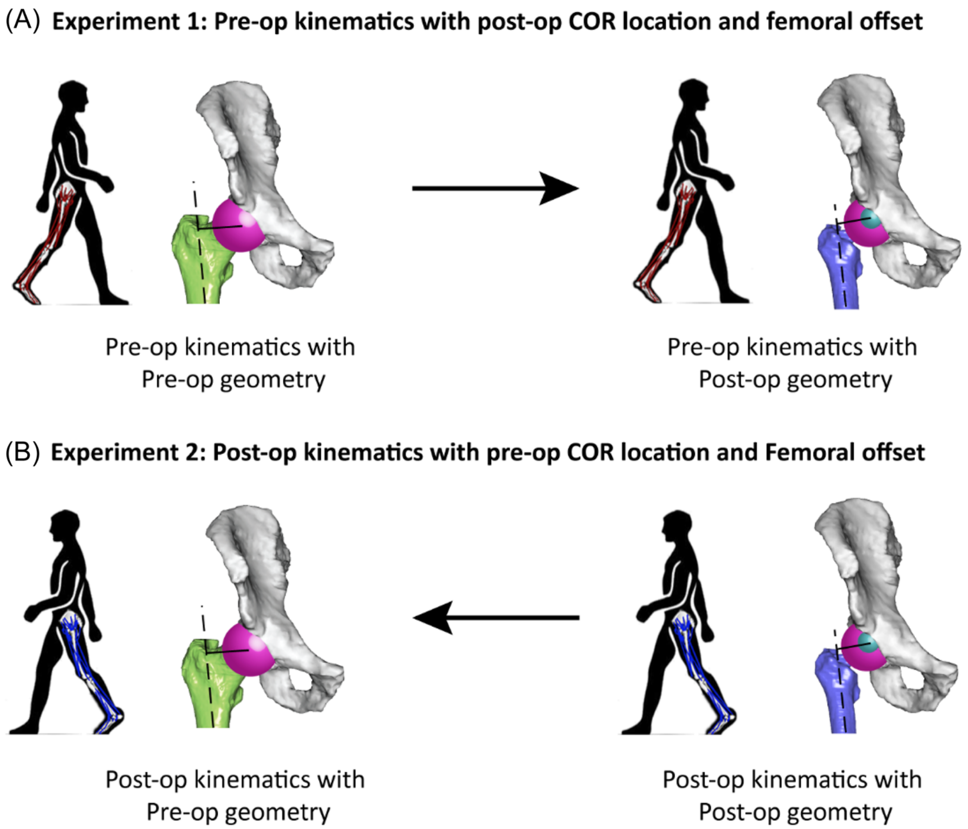

FIGURE 1 (A) Preoperative gait kinematics were used as inputs to calculate muscle and joint contact forces, while hip joint geometry (centre of rotation and femoral offset) was set to the postoperative location. (B) Postoperative gait kinematics were used, while the hip joint geometry was set to the preoperative location. [Color figure can be viewed at wileyonlinelibrary.com]

To compare the COR location from pre- to post-surgery, which were directly estimated from the CT scan taken at the corresponding time point, the 3D reconstructions had to be aligned. For this, anatomical landmarks were manually located on the anterior superior iliac spines, posterior superior iliac spines, and left and right pubic symphysis, and then aligned using an iterative closest point registration in NMSBuilder[21] (Figure 2A). Second, spheres were fitted to markers placed on the surface of the femoral heads in NMSBuilder (Figure 2B). For the first two experiments the relative change in the centre of the pre- and postoperative femoral heads were used to update the models. To determine femoral offset, the pelvis was first aligned in the coronal plane in Matlab 2019a (R2019a, Mathworks) using the most inferior point of the ischium, and the position of the femora were adjusted accordingly to maintain its relative position in the pelvis. Subsequently, the femoral axes were established by manually picking four coordinates along the medial and lateral aspects of the femora and projecting a line intersecting the midpoint of each pair of markers in Matlab. Acetabular offset was calculated as the distance between the centre of the ASIS markers and the COR. Femoral offset was calculated as the perpendicular distance between the centre of the femoral head and the intersecting point of the femoral axes (Figure 2C). For both experiments, the difference between the pre- and postoperative acetabular and femoral offsets for the case hip were used to update the musculoskeletal models (see Section 2.4). The abductor lever arm was defined as the sum of change in acetabulum offset and femoral offset, e.g. reducing acetabulum offset by 2 mm and increasing femoral offset by 2 mm = 4 mm increase in abductor lever arm.

2.3 | Gait analysis

Each participant underwent 3D gait analysis the pre- and postoperative time point to capture the motion of their pelvis and lower limbs during walking. One investigator (JB) placed skin-surface markers atop prominent anatomical landmarks on the pelvis and lower limbs.[22] A 10-camera motion analysis system (Vicon) recorded skin-surface marker trajectories (100 Hz) and two ground-embedded force platforms (Advanced Mechanical Technology Inc.) recorded ground reaction forces (2000 Hz). Marker trajectories and ground reaction forces were processed using MOtoNMS[23] in MATLAB R2018a (The MathWorks Inc).

2.4 | Musculoskeletal modeling

For each participant, the skeletal geometry of the open-source Gait2392 generic model[24] was scaled to their mass and anthropometry using the Musculoskeletal Atlas Project (MAP) Client.[25,26] A combination of pelvis

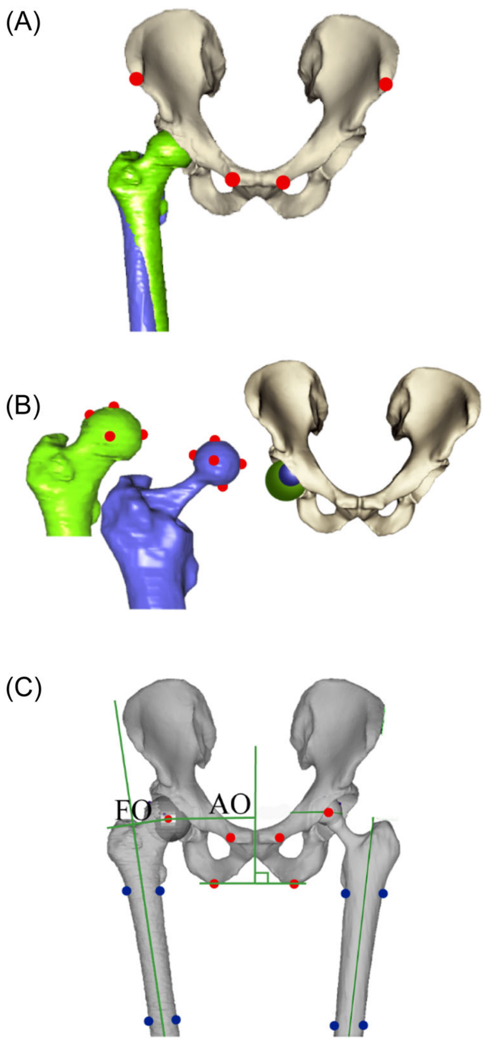

FIGURE 2 (A) Iterative closest point registration was used to align pre- and postoperative models based on manually selected points on the anterior superior iliac spines, posterior superior iliac spines and pubic tubercles in NMSBuilder. (B) Spheres were fitted to markers placed on the surface of the femoral heads in NMSBuilder; green: pre-op; blue: post-op. (C) Femoral offset measured as the distance between the centre of the femoral head and the axes of the femur. Acetabulum offset was measured as the distance between the midline of the pelvis and the femoral head centre. Abductor lever arm = FO + AO. [Color figure can be viewed at wileyonlinelibrary.com]

and femur reconstructions from CT were combined with skin-surface markers to perform a principal component morphing of the MAP Client pelvis, femur, and shank. Bone shape and, therefore, muscle insertions were not tailored to the individual. The trunk and feet were linearly scaled in OpenSim as statistical shape models for these segments are not currently implemented in the MAP Client.

For each walking trial, model general coordinates (i.e., joint rotations and translations) and abductor muscle forces were calculated using the inverse kinematics and static optimization tools in OpenSim, respectively.[27] The musculoskeletal model used in this study defines the hip abductors with three separate bundles. The sum of all three was used to represent the hip abductor muscle force. The model kinematics and muscle forces were then used to determine hip contact forces using the joint reaction analysis tool in OpenSim. Hip contact forces were normalized to bodyweight (BW)[28] and expressed in the femoral reference frame.[29] The outcome variables of interest were the maximum (vector sum) abductor muscle force (in Newtons [N]) and hip contact (vector sum) force (in N and normalized to body weight [BW]).

2.5 | Statistical analysis

Before completing formal statistical analyses, the distributions of the data were confirmed normal using Shapiro–Wilk tests. Paired samples *t*-tests were used to examine differences in the peak hip contact force and hip abductor muscle force when the preoperative model was adjusted so that the COR and femoral offset reflected changes made during surgery (Experiment 1). The same statistical analysis was used for the postoperative model when the COR was reverted to the preoperative location, while retaining the postsurgical kinematics and kinetics compared to retaining the postsurgical COR (experiment 2). A *p*-value of <0.05 was considered statistically significant. Cohen's *d* effect sizes are presented alongside *p*-values.

Both experiments included changes in the location of the COR along all three orthogonal directions (anterior-posterior, proximal-distal, and medial-lateral). To delineate the effect of each direction on hip contact forces, linear regression analyses were performed to determine the relationships between changes in the COR and peak resultant hip contact force. First, a univariate linear regression analysis was performed with each of the three orthogonal directions as independent variables. Second, backward linear multivariate modeling was performed to determine the predictive value of COR changes on hip contact forces, only including parameters reaching a *p*-value of <0.10 in the univariate analysis. All analyses were performed using IBM SPSS Statistics (version 28, IBM).

3 | RESULTS

Fifty-one of 221 patients undergoing primary THA during the indexed period met the eligibility criteria and consented to participate in this study. Data from 35 participants were used in this study after completing the preoperative procedures and remaining in the study at 6 months (23 male, 12 female; mean ± standard deviation for age: 66 ± 14 years; height: 1.7 ± 0.1 m; mass: 81.9 ± 16 kg; body mass index: 29 ± 5 kg/m^2).

3.1 | Surgical changes to geometry during total hip arthroplasty

Relative to the preoperative location, the COR was commonly displaced medially and superiorly during surgery (Table 1). Relative to preoperative values, acetabulum offset was typically reduced (83% of

TABLE 1 Mean (range) displacement of centre of rotation (COR) from pre-to postsurgery

	Anterior-posterior (X)		Proximal-distal (Y)		Medio-lateral (Z)	
	Anterior	Posterior	Proximal	Distal	Lateral	Medial
Post-surgery						
COR displacement (mm)	3.6 (1.1–7.5)	2.3 (0.4–5.7)	2.9 (0.1–11)	4.0 (0.3–8.6)	1.3 (0.3–2.2)	7.4 (0.2–19)
Cases (%)	41	59	56	44	19	81

TABLE 2 Changes in abductor lever arm from pre-to postsurgery

	N (%)*	Mean change (mm)	SD change (mm)	Range (mm)
Increased abductor lever arm	27 (77%)	15	9	1–34
Decreased abductor lever arm	8 (23%)	−3	2	−2 to −6

*Percentage of the cohort of patients showing an increase or decrease in abductor lever arm.

patients showed a reduction) (with a mean difference of −6 ± 7 mm. Femoral offset was typically increased (83% of patients showed a reduction) with a mean difference: 8 ± 7 mm. The changes in abductor lever arm are presented in Table 2.

3.2 | Effect of hip joint geometry with preoperative kinematics (Experiment 1)

Using preoperative gait kinematics, together with the preoperative COR location and femoral offset, peak hip abductor force before surgery was 906 ± 330 N. Mean peak hip contact force before surgery was 2389 ± 862 N (2.8 ± 0.8 BW). When the COR and femoral offset were set in the model to reflect changes caused by THA and selecting for only the patients that had an increase in their hip abductor lever arm ($n = 27$), paired samples *t*-test revealed a significant reduction in peak hip abductor muscle force (mean difference: −251 N, 95% confidence interval [CI]: 165–337 N, Cohen's $d = 1.2$, $p < 0.001$). Similarly, a reduction in peak hip contact force was observed (mean difference: −422 N, 95% CI: −664 to −181 N [−0.6BW, 95% CI: −0.86 to − 0.22 BW], Cohen's $d = 0.74$, $p = 0.003$) (Figure 3). Eight patients (23%) showed an increase (11%) in hip contact force (mean difference: 235 N, 95% CI: 88–383 N [0.33 BW, 95% CI: 0.57–1.1 BW], Cohen's $d = 1.3$, $p = 0.007$) (Figure 3).

The medial-lateral and proximal-distal changes to the COR were significantly correlated with changes in peak hip contact force ($r = 0.64$, $p < 0.001$ and $r = −0.39$, $p = 0.014$, respectively). Only medial-lateral and proximal-distal COR changes were retained in the multivariate regression model, predicting 63% of the variance in the peak hip contact force ($p < 0.001$). The COR medialisation alone predicted 40% of the variance in hip contact force. For each millimeter of COR medialisation, peak hip contact force was reduced by 26 ± 4 N. For each millimeter of increase in superior location, the peak hip contact force reduced by 10 ± 6 N.

3.3 | Effect of hip joint geometry with postoerative gait kinematics (Experiment 2)

Using postoperative gait kinematics together with the postoperative hip geometry (i.e., COR location and femoral offset), peak hip abductor force after surgery was 942 ± 310 N. The mean peak hip contact force at 6-months post-surgery was 2840 ± 840 N (3.48 ± 0.86 BW). When the hip geometry (i.e., COR location and femoral offset) was set to its preoperative geometry in the model, and considering only the patients where the abductor lever arm was reduced in this experiment, paired samples *t*-test revealed a significant increase in the peak hip abductor muscle force (mean difference: 250 N, 95% CI: 162–337 N, Cohen's $d = 1.2$, $p < 0.001$). Similarly, the peak hip contact force increased (mean difference: 324 N, 95% CI: 155–491 N, Cohen's $d = 0.8$, [0.4BW, 95% CI: 0.18–0.61], $p = 0.001$) (Figure 4). However, for the eight patients with a larger abductor lever arm preoperatively compared to postoperatively, no differences in the peak hip abductor muscle force ($p = 0.26$) or peak hip contact force were observed ($p = 0.32$) when set to the preoperative geometry in the model.

4 | DISCUSSION

The objective of this study was to investigate if surgical change to the acetabular offset and femoral offset following primary THA was associated with changes in abductor muscle and hip contact forces. Medial and superior placement of the COR during THA was associated with a reduction in hip joint contact force, of which medialisation was the strongest predictor, explaining 40% of the variance in contact force. Medialising the COR and increasing femoral offset reduced the required abductor muscle force by 28%, resulting in a 17% reduction in the hip joint contact force.

The postoperative estimates of hip contact force (post-operative hip joint geometry and kinematics) increased (19%)

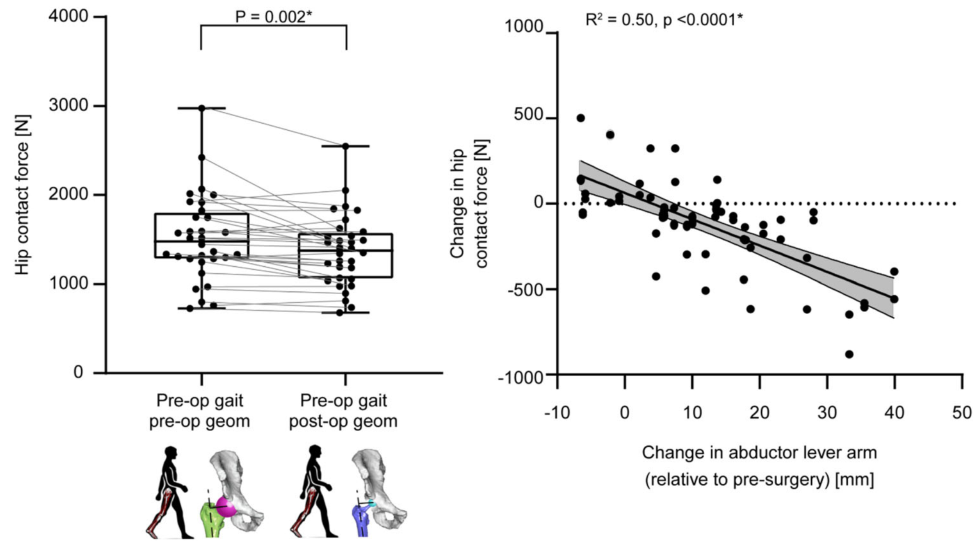

FIGURE 3 Left panel: Effect of surgical change to the COR and femoral offset on the peak hip contact force compared with the preoperative valued created by using preoperative gait kinematics and hip joint geometry. Right panel: Change in abductor lever arm (relative to presurgery) and its association with hip contact forces. COR, centre of rotation. [Color figure can be viewed at wileyonlinelibrary.com]

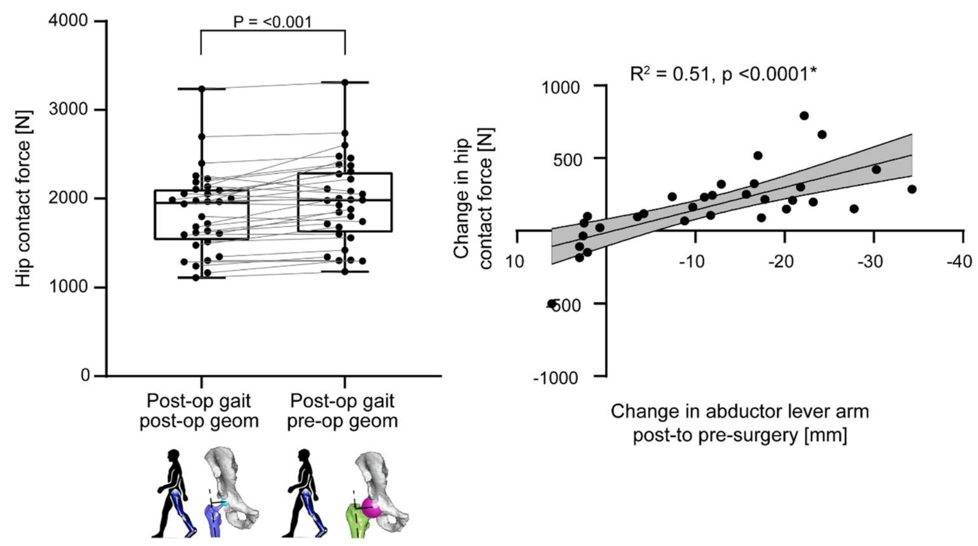

FIGURE 4 Long-term effect (at 6 months) on the peak hip contact force if preoperative hip geometry is used, along with postoperative gait kinematics, in the model compared to the postoperative estimate that used both the postoperative gait kinematics and hip joint geometry (green). [Color figure can be viewed at wileyonlinelibrary.com]

compared with preoperative hip contact force (preoperative hip joint geometry and kinematics). This suggests surgical changes to hip joint geometry did not achieve its goal.[30,31] However, the analysis of thought Experiment 2 revealed that if hip geometry remained unchanged, the abductor muscles would have to produce a significantly larger force (250 N, 27%), which in turn would further increase the hip contact force (324 N, 11%). This indicates the larger hip contact forces observed postoperatively were driven by changes in walking gait, and that increasing the abductor lever arm is important to help attenuate these larger hip joint forces postoperatively.[3]

The observed biomechanical benefit from increasing the abductor lever arm in this study is consistent with previous findings.[4,11,19,20] However, the magnitude of the effects on the hip abductor muscle and hip joint contact force was larger in this study (~15% and 7%, respectively),[11] which is likely attributed to this study looking at the combined effect of changes in acetabular and femoral offset, as opposed to only the femoral offset. For the eight patients that had a reduction in the abductor lever arm distance post-operatively, a significant increase in hip contact force was observed using their preoperative gait pattern. However, the reverse effect was not observed using the postoperative gait pattern, indicating that the effect of a reduced abductor lever arm may be more consequential with poorer gait function.

The magnitude of change in muscle and joint contact forces because of surgery can be contextualized considering other strategies, such as reducing body mass. In this study, the effect of surgery reduced the abductor muscle force by −250 N. This effect is equivalent to a patient losing 13 kg, assuming a 1:2 ratio between a reduction in body mass and reduction in force required by the hip abductor muscle force.[32]

Although this study emphasizes the importance of medialising the acetabular cup and using a high-offset stem to increase the biomechanical lever arm, the amount of cup medialisation is limited by two factors. First, excessive medialisation of the acetabular component can lead to undesirable complications and side effects. Over reaming in the medial direction may lead inadequate cup stability through the loss of the rim fit. In excessive cases, loss or fracture of the medial wall can result in catastrophic failure of the acetabular implant either intraoperatively or, if unrecognized intraoperatively, in first postoperative day as weightbearing is resumed. Although such failures are more likely in cases with boor pone quality, for example, people with osteoporosis or renal osteodystrophy, they could happen in any case with aggressive over reaming. Medialisation of the cup could also lead reduced hip range of motion through stem-neck impingement against the bony rim of the acetabulum. Second, balance of the overall hip offset in cases with acetabular medialisation is restricted in by the limited options of offset for each femoral implant. If this is not factored in during preoperative planning, the result might be medialisation of the cup with an overall decreased offset of the hip and therefore an ineffective leaver arm of the abductors.

The findings in this study must be viewed considering certain limitations. First, this study aimed to determine the effect of changes in hip joint geometry on hip joint forces independent of, and together with, changes in gait function. However, underlying skeletal geometry and kinematics cannot be de-coupled given kinematics (e.g., joint motions) are influenced by geometry. Second, thought Experiment 2 set the COR and femoral offset to the preoperative locations, while the 6 months motion capture data were used to compute muscle and joint contact forces. This carried an underlying assumption that patients could produce gait kinematics similar that seen at 6 months post-surgery with preoperative geometry. Finally, this study did not include other important geometrical changes such as femoral anteversion and leg length discrepancy, which have been shown to significantly influence muscle and joint contact forces.

5 | CONCLUSION

We identified that pre- to post-THA, hip contact forces increased, which is likely a result of improved gait. If hip geometry (acetabular offset and femoral offset) remains unchanged from preoperative, the abductor muscles produce a significantly larger force resulting in larger hip joint contact forces. However, the medialisation of the hip COR associated with reaming during THA attenuates the increase in hip abductor muscle force associated with hip kinematics.

AUTHOR CONTRIBUTIONS

Jasvir S. Bahl conceived the study, collected the data, performed the analysis, and drafted the manuscript. Dominic Thewlis, John B. Arnold, Mark Taylor, and Lucian B. Solomon conceived the study, assisted with the analysis, drafted the manuscript, and supervised the study; David J. Saxby assisted with the analysis and drafted the manuscript. All authors approved the final draft before submission.

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