Hip joint contact pressure and force: a scoping review of in vivo and cadaver studies

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Aims

Research on hip biomechanics has analyzed femoroacetabular contact pressures and forces in distinct hip conditions, with different procedures, and used diverse loading and testing conditions. The aim of this scoping review was to identify and summarize the available evidence in the literature for hip contact pressures and force in cadaver and in vivo studies, and how joint loading, labral status, and femoral and acetabular morphology can affect these biomechanical parameters.

Methods

We used the PRISMA extension for scoping reviews for this literature search in three databases. After screening, 16 studies were included for the final analysis.

Results

The studies assessed different hip conditions like labrum status, the biomechanical effect of the cam, femoral version, acetabular coverage, and the effect of rim trimming. The testing and loading conditions were also quite diverse, and this disparity limits direct comparisons between the different researches. With normal anatomy the mean contact pressures ranged from 1.54 to 4.4 MPa, and the average peak contact pressures ranged from 2 to 9.3 MPa. Labral tear or resection showed an increase in contact pressures that diminished after repair or reconstruction of the labrum. Complete cam resection also decreased the contact pressure, and acetabular rim resection of 6 mm increased the contact pressure at the acetabular base.

Conclusion

To date there is no standardized methodology to access hip contact biomechanics in hip arthroscopy, or with the preservation of the periarticular soft-tissues. A tendency towards improved biomechanics (lower contact pressures) was seen with labral repair and reconstruction techniques as well as with cam correction.

Article focus

- Femoroacetabular contact pressures and forces have been analyzed in distinct hip conditions, with different procedures, and used diverse loading and testing conditions.
- A structured review is needed to clarify the available evidence for the hip contact pressure and force in cadaver and in vivo studies.

Key messages

- The hip contact peak pressures ranged from 2 to 9.3 MPa.
- A tendency to improved biomechanics was seen with cam correction, labral repair, and reconstruction.

Bone & Joint Research

- There is no specific medical device to measure hip contact pressure with the preservation of the periarticular soft-tissues and joint capsule.
- Further research should focus on how intraoperative measurement of contact force and pressure can be used to confirm the restoration of joint biomechanics in hip preservation surgery.

Strengths and limitations

- We summarize the available evidence for hip contact pressure and force in cadaver and in vivo studies.
- The main limitation of this scoping review is related to the heterogeneity of the included studies due to the different studied conditions, testing and loading settings.

Introduction

Several hip conditions are due to abnormal biomechanics, leading to premature articular damage and malfunction. Therefore, understanding hip biomechanics is extremely important, not only for assessing joint function but also for hip preservation and reconstruction surgery.

Besides the morphological analysis of the hip joint, there are several tools to assess hip biomechanics for research purposes, such as hip contact pressures (CP) and forces (CF). These parameters have been estimated in different types of studies, such as cadaver studies with pressure monitoring devices,[1-4] clinical in vivo measurements with an instrumented endoprosthesis,[5,6] finite element analysis (FEA),[7-11] or discrete element models (DEA).[12,13]

Research performed in cadavers analyzed femoroacetabular CP in distinct hip conditions, with different procedures, and used diverse loading and testing conditions. They also assess how different surgical interventions influence femoroacetabular forces and CP. Intraoperative assessment of femoroacetabular CP and forces, before and after deformity correction, can confirm the improvement of biomechanics with the surgery and might decrease the need for revision surgery due to residual deformity or abnormal mechanics.

The instrumented prosthesis studies recruited older patients with different activity patterns compared to younger patients with femoroacetabular impingement syndrome (FAI), and they measured the pressure in metal on the cartilage surface rather than cartilage on the native cartilage joint.

As in vivo data on the cam FAI biomechanics are scarce, FEA studies have been used as a surrogate.[7,10] A systematic review of finite element simulations demonstrated an increase in CP in the anterosuperior region of the acetabular cartilage.[11]

This scoping review aims to identify and summarize the available evidence in the literature for hip CP and CF in cadaver and in vivo studies, and how joint loading, labral status, femoral and acetabular morphology can affect these biomechanical parameters.

Methods

We used the PRISMA extension for scoping reviews for this literature search.[14-16] A thorough electronic database search including studies published until 1 January 2022 was performed by three authors (PD, SRG, AG) who independently searched several databases (PubMed, Scopus, and Web of Science). The study protocol was registered, and the description of the search strategy and screening process can be found in the Open Science Framework.[17] This literature search was developed around 'population' (femoroacetabular impingement, FAI, FAIS, cam), 'interventions' (arthroscopy, surgery, reconstructive surgery), 'context' (in vivo, cadaver), and the measurements of interest (biomechanics, contact pressure, stress, force).

We used the following search terms in different combinations:

(Femoroacetabular impingement OR FAI OR FAIS OR cam) AND (arthroscopy OR surgery OR reconstructive surgery) AND (in vivo OR cadaver) AND (hip OR hip joint) AND (biomechanics OR pressure OR stress OR force).

(Femoroacetabular impingement OR FAI OR FAIS OR cam) AND (arthroscopy OR surgery OR reconstructive surgery) AND (hip OR hip joint) AND (biomechanics OR pressure OR stress OR force).

The reviewing process was limited to publications in English. The sciwheel reference manager (Sage, UK) was used to remove duplicates from multiple database searches.

A qualitative and quantitative synthesis of the included articles was conducted and extracted data with the following details: type of study, authors, year of publication, scope, condition, number of participants, specimen preparation, type of sensor and testing system used, parameters evaluated, location of the measurements within the hip, applied load, hip position, available results (CP, contact area, and peak force), and the effect of the surgical intervention.

Results

After the duplicates were removed, 702 citations were identified with the electronic database search and review of the study's references. Based on the title and abstract, 679 records were excluded because they did not meet the inclusion criteria (e.g. studies on FEA or DEA, papers with instrumented prostheses, and research that did not evaluate joint pressure, force, or stress) (Figure 1). After screening, 16 studies were included for the final analysis. Relevant results and study details are presented in Table I.

Type of study

A total of 15 studies were performed on cadaver specimens using an open approach, and most of the cadaveric studies stated that the extracapsular soft-tissues and capsule were excised. Only a single study reported an in vivo measurement of the femoroacetabular CP in hip arthroscopy.[28]

Some studies focused on how FAIS affects joint CP and CF,[2,3,29] while others evaluated these parameters in cadaveric joints with no reported morphological deformity.[4,18–26]

Scope

Eight studies addressed the contact stress distribution.[18–25] Four papers studied how the labrum status affects hip CP,[1,4,26,27] and two discussed the cam biomechanical effect.[2,28] One study examined the effect of rim trimming,[3] and another the role of femoral version.[29]

Type of sensor

Fujifilm Prescale (Fujifilm, Japan) was used in six studies to assess the contact area and contact stress in the hip joints.[21,23–26,29] A piezoresistive pressure mat was used in five studies,[1–4,27] and permitted the assessment of the contact area, CP, and

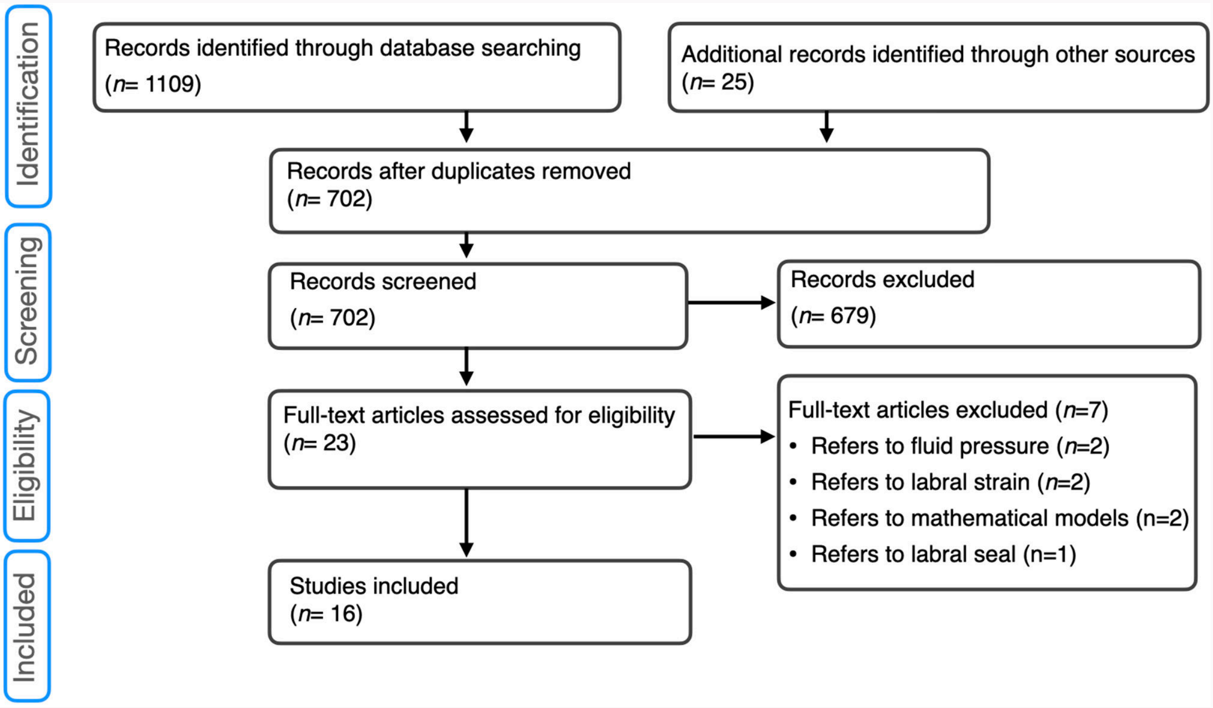

Fig. 1
PRISMA flowchart.

peak force. Specifically, the Tekscan model 5101 was used in four of these studies, as a flat quadrangular matrix of 111.8 mm.

A small piezoresistive sensor was used in two studies,[19,20] one study used a piezoelectric pressure transducer,[22] and a further two studies used a displacement transducer and a fibre optic microtransducer.[18,28]

Location of the sensors

The number and the location of the sensors were quite different among the studies. In 12 studies, the sensor was placed in the articular space between the femoral head and the acetabular articular cartilage, in three studies the sensors were located within the acetabulum,[18,19,22] and in another study, the sensors were in the femoral head.[20]

Biomechanical parameters

Different hip biomechanical properties were analyzed, and for this review, we focused on the hip CP, contact area, and peak forces. Four studies presented normalized CP and peak force data without reference to the absolute values.[1-4]

Applied load

The applied load in the cadaveric works had considerable differences. In some studies, a fixed load was used (350, 500, 700, or 1,334 N) while others used a progressive physiological load or a load according to different activities (from half to four times the body weight). In the only in vivo study, the load was not quantified but could change with progressive hip flexion.[28]

Activities and hip position

In three studies, the authors tried to reproduce some instants of the walking cycle.[22,23,25] Other studies evaluated the hip parameters in different degrees of joint flexion and extension, abduction and adduction, and rotation,[1,3,4,19,20,27–29] while others accessed the hip parameters in just one position.[2,18,21,24,26]

For the neutral alignment, the specimen was mounted in a testing machine in the anatomical position with 0° of hip flexion and didn't account for the pelvic tilt.[30] In three studies the acetabulum was positioned with a vertical acetabular angle of 40° and pubic-femoral neck angle of 140°.[1-3]

There was a significant variation of pressures recorded for different hip positions.[19] Peak pressure was in the ventrosuperior surface in the four phases of the gait cycle.[25] CP was significantly higher at midstance than at heel-strike or toe-off.[25] For all labral conditions (intact, repaired, and reconstructed) the highest average maximum pressure occurred under hip external rotation.[27] Normalized CP and peak force in different hip positions (neutral, 20° of extension, and 60° of flexion) did not show differences between labral state.[1] Satpathy et al[29] studied the effect of femoral retroversion and hip internal rotation, and concluded that 10° of hip internal rotation had no significant effect on the posteroinferior joint peak forces.

Contact pressure

We found a wide variation of pressures recorded in different hip positions and distinct acetabular sites. The pressure was not uniform over the loaded area, and several studies registered higher pressures in the anterior and superior segments of the acetabulum.[18,21–25,29]

For the different studies, the average mean pressures were 1.5 MPa,[18] 2.9 MPa,[20] 3.5 to 4.4 MPa,[26] and with an intact acetabular rim of 0.1 MPa.[3] The average peak pressures were 3.5 MPa,[18] 8.8 MPa,[20] 2 MPa,[21] 5.3 to 8.5 MPa,[22] 8.3 MPa,[23] 5.4 to 7.7 MPa,[25] 6.3 to 7.1 MPa,[26]

Table I. Relevant results of the included studies.

Type of study	Author, Year	Scope/condition	Sample size and specimen details	Preparation	Testing and loading conditions						Results			
				Preparation	Sensor	Testing system	Parameters evaluated	Area/location	Load	Hip position/activity	CP	Contact area	Peak force	Effect of surgery
Normal morphology														
Cadaver/open surgery	Day 1975[18]	CP distribution under physiological loads	17 patients; 9 F/ 18 M; mean age 58 yrs; mean BW 54 kg; no cartilage fibrillation	Soft tissues other than the cartilage removed	Displacement transducer	Testing materials machine; vertical loading	Pressure; load deflections curves of the cartilage thickness	Five transducers in the acetabulum	0 to 3 times BW of the cadaver	Standing position	Average peak CP at maximum load 3.5 MPa; average mean CP at maximum load 1.5 MPa; highest CP 4 to 5 MPa	CP is not uniform over the loaded area; load is carried anteriorly and posteriorly on the acetabulum at the average pressure within the hip		N/A
Cadaver/open surgery	Mizrahi 1981[19]	Direct measure of CP and CP distribution	12 patients; 1 F/ 11 M; mean age 36 yrs	Joint disarticulation and soft-tissues removed	Subminiature Kyowa pressure sensors (type P5-IOKA) in 3 hips; strain gauge (Kyowa type KFC-2-Cl) in 9 hips	Instron testing machine	CP	Four subchondral acetabular sensors	500 N	Neutral, flexion 20°, extension 20°, abduction 20°, adduction 20°, lateral rotation 20°, and medial rotation 20°	Wide variation of CP recorded at any particular site; major pressures in the anterior and posterior acetabulum; lowest pressures found at the zenith of the joint			N/A
Cadaver/open surgery	Brown 1983[20]	CP distribution and direct estimates of the contact stress in the natural hip	17 patients	Capsule removed	Miniature piezoresistive transducer	Instron Model 1122	Contact stress	24 sensors in the femoral head	Load up to 2,700 N	Neutral, 10°, 20°, and 30° of flexion	Average peak local stress at maximum load 8.8 MN/m^2; average mean local stress at maximum load 2.92 MN/m^2; lack of influence of the flexion angle on the contact stress distributions	Irregular area with weak anteroposterior ridge		N/A
Cadaver/open surgery	Miyanaga 1984[21]	CP and CA distribution under compression load	5 patients; mean age 62 yrs	NR	Fuji prescale film; contact area measured by casting method	Instron type testing machine (TOM-500)	Load-deformation curve; pressure distribution; CP	Between the femoral head and acetabulum	500 N, 1,000 N and 1,500 N	Neutral position	Peak pressure of 2 MPa until a load of 1,000 N; peak pressure at the anterior and posterior parts; magnitude was larger in the anterior part	Maximum CA was 14 to 16 cm^2; at 200 N load, the anterior and posterior portions were the main contact areas; over 500 N load, the total cartilage surface was in contact; contact area increased as load increased		N/A
Cadaver/open surgery	Adams 1985[22]	CP in the walking cycle	9 patients; 4 F / 5 M; mean age 57 yrs; mean BW 66 kg	NR	Piezoelectric pressure transducers (3 mm in diameter)	Hounsfield Tensometer type E	Pressure	11 transducers in the acetabulum	100 N to 3,600 N	Six instants in the walking cycle	Highest pressure from 5.3 to 8.6 MPa, all in the heel off configuration; highest pressures in the transducers over the zenith of the femoral head and in the configuration heel off			N/A
Cadaver/open surgery	Afoke 1987[23]	CP distribution in the walking cycle	5 patients; 3 F / 2 M; mean age 76 yrs; mean BW 64 kg	Soft-tissue and the labrum removed	Fujifilm Prescale (Low Grade 1 to 10 MN/m^2)	Servo-controlled hydraulic testing machine	CP	Between the femoral head and acetabulum	3.3 (heel stryke), 1.3 (flatfoot) and 4 times (toe-off) BW	Heel strike (27° flexion), flatfoot (0° neutral) and just before toe-off (18° extension)	Average maximum CP at 27° Flexion 8.3 MPa, at 0° 5.8 MPa and at 18° extension 7.8 MPa; maximum pressure 10 MPa; area of high pressure in the anterosuperior segment	Maximum CA occurred in extension		N/A
Cadaver/open surgery	Bay 1997[24]	CP and CA distribution within the hip joint with whole pelvis and isolated hip joint	7 patients; 2 F / 2 M; mean age 72 yrs	Pelvis or hip joint	Fujifilm Prescale (low sensitivity 2.5 to 10 MPa)	Instron Model 1122	CP and CA	Between the femoral head and acetabulum	Abduction force until estimated BW	Femoral shaft in 15° of adduction relative to the pelvis	Mean CP increased 28% in the superior acetabulum for the explanted configuration	CA for the explanted configuration decreased 60 and 65% in the posterior and anterior regions and showed an increase in the superior acetabulum; contraction of the acetabulum whitin the pelvis	Contact force increased in the superior acetabulum, and decreased in anterior and posterior walls,	N/A

(*Continued*)

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Type of study	Author, Year	Scope/condition	Sample size and specimen details	Preparation	Testing and loading conditions						Results			
				Preparation	Sensor	Testing system	Parameters evaluated	Area/location	Load	Hip position/activity	CP	Contact area	Peak force	Effect of surgery
												squeezes the femoral head, causing CP to develop in the peripheral regions	for the explanted configuration	
Cadaver/open surgery	von Eisenhart 1999[25]	CP and CA distribution for different phases of gait	8 patients; mean age 45 yrs	Joint desarticulation; labrum intact	Fujifilm Prescale (low sensitivity 2.5 to 10 MPa)	Zwick Model 1445	Join space, cartilage thickness, CP, and PD	Between the femoral head and acetabulum	80% to 345% of BW	Heel-strike, midstance, heel-off, and toe-off	Maximum CP: 6.4 ± 1.8 MPa at heel-strike, 7.7 ± 2 MPa at midstance, 6.4 ± 1.3 Mpa at heel-off, and 5.4 ± 1.7 MPa at toe-off; highest CP was 9.8 MPa at midstance; pressure peak in the ventrosuperior surface in the four phases	At minimal load there is contact at the ventrosuperior and dorsoinferior aspects of the lunate surface; at physiological loads full contact is established during midstance and heel-off		N/A
Labrum														
Cadaver/open surgery	Konrath 1998[26]	Labrum; role of the labrum and transverse ligament in load transmission	17 patients; 5 F / 4 M; mean age 45 yrs	Capsule removed	Fujifilm Prescale (Low range 2.5 to 10 MPa)	Instron testing machine	CP, CA, and joint reaction force	Between the femoral head and acetabulum	BW of the cadaver; mean applied load 2,060 ± 890 N	Adduction 15° and internal rotation 5° to 10°	Maximum mean CP with intact labrum: anterior 6.5 Mpa, superior 7.1 MPa and posterior 6.2 MPa; mean CP with intact labrum: anterior 3.9 MPa, superior 4.4 MPa, and posterior 3.5 MPa; joint-reaction forces 2,350 ± 1,460 N in the intact hips	Peripheral pattern of loading was not grossly changed after removal of the transverse ligament or the labrum		Mean and maximum CP in the posterior acetabulum were significantly decreased after labrectomy; no significant changes in the anterior or superior acetabulum
Cadaver/open surgery	Lee 2015[4]	Labrum; biomechanics with a labrum-intact, labrum-deficient, and labrum-reconstructed	10 patients; 6 F /4 M; mean age 59 yrs	Extracapsular soft-tissue, capsule, and ligamentum teres removed	Piezoresistive load sensor (Model 5101; Tekscan)	MTS Insight 5	CA, CP, and PF; values normalized to the intact state	Between the femoral head and acetabulum	700 N (three-quarters the BW)	20° of extension and 60° of flexion	CP significantly increased after labral resection with extension and flexion and subsequently improved after reconstruction; no differences between either graft type in relation to CA, CP, or PF after labral reconstruction	Significant decrease in the CA at extension and flexion after labral resection that improved after reconstruction; CA after reconstruction rarely reached 100% of the native intact labrum	PF demonstrated less of an association with the differing labral states	Large decreases in CA and increases in CP; labral reconstruction improved biomechanical measurements; some remained significantly different compared with the native intact labrum
Cadaver/ open surgery	Angsutanasombat 2018[27]	Labrum; develop a hip simulation machine and test the labral status; labrum intact, repaired, and reconstructed	20 patients	Dissected cadaveric pelvis	K-scan sensor, Tekscan	Hip simulation machine	CP	Between the femoral head and acetabulum	350 N (half the BW)	Neutral; abduction 20°; adduction 10°; flexion 20°; extension 20°; internal rotation 20°; external rotation 20°	Highest CP (around 600 kPa) occurred under external rotation; labral reconstruction reduced the CP in all conditions except in flexion and internal rotation; labral repair reduces the pressure in all conditions except adduction			Labral reconstruction and labral repair reduced the CP
Cadaver/open surgery	Suppauksorn 2020[1]	Labrum; biomechanics with an the intact labrum, torn labrum, labral	8 patients; 5 F / 5 M; mean age 62 yrs; mean BMI 24; mean α angle 56°	All extracapsular soft-tissues excised, including the	Piezoresistive load sensor (Model 5101; Tekscan)	MTS Insight 5	CA, CP, PF, and suction seal; values normalized to the intact state	Between the femoral head and acetabulum; full joint map and along the	700 N (three-quarters the BW)	Neutral, 20° of extension, and 60° of flexion	Normalized CP in all 3 positions did not show differences between labral state	Labral reconstruction had the smallest CA; normalized ROI contact area in extension and flexion decreased in the labral repair and reconstruction	Although not statistically significant, PF were higher in labral reconstruction;	Trends with the labral repair having lower CP and higher CA than the reconstruction

(*Continued*)

(*Continued*)

Type of study	Author, Year	Scope/condition	Sample size and specimen details	Preparation	Testing and loading conditions						Results			
				Preparation	Sensor	Testing system	Parameters evaluated	Area/location	Load	Hip position/activity	CP	Contact area	Peak force	Effect of surgery
		repair, and labral reconstructions		iliofemoral ligament.				labrum (11- to 2-o'clock position)					normalized PF in all 3 positions did not show differences between labral state	
FAI morphology														
In vivo/ arthroscopy	Kaya 2017[28]	Cam; CP in hip arthroscopy	NR	Interportal capsulotomy	Fiberoptic microtransducer (Camino intraparenchymal device)	In vivo	CP	Between the femoral head and the acetabulum below the anterior-inferior iliac spine	Progressive hip flexion	0° and 90° of flexion	NR			Correction of cam-type deformity prevented the elevation of CP during forceful hip flexion
Cadaver/open surgery	Suppauksorn 2020[2]	Cam; effect of a cam lesion, partial cam resection, and complete cam resection	8 patients; 1 F / 7 M; mean age 62 yrs; mean BMI 25; mean α angle 62°; mean LCEA 35°	All extracapsular soft tissues and the capsule excised; α angle > 55° and intact labra	Piezoresistive load sensor (Model 5101; Tekscan)	MTS Insight 5	CA, CP, and PF; values normalized to the native state	Between the femoral head and acetabulum; pressure map from the 11-to 2-o'clock position	700 N (three-quarters the BW)	Flexion 80° and internal rotation 15°	Reduction in CP in the partial (6.3%) and complete cam resection (17.4%) groups compared with the intact group	No statistically significant differences in normalized CA between the 3 conditions	PF was not different between groups; higher PF average in the partial group compared with the complete group	Normalized CP of complete cam resection are lower than those of the native cam state as well as partial cam resection
Cadaver/open surgery	Bhatia 2015[3]	Pincer; effect of sequential rim trimming	6 patients; mean age 57 yrs; mean LCEA 36°	Capsule and labrum removed; mean LCEA 35.7°	Piezoresistive load sensor (Model 5101; Tekscan)	MTS Insight 5	CA, CP, and PF; values normalized to the native acetabular state	Between the femoral head and acetabulum	700 N (three-quarters the BW)	Extension 20° and flexion 60°	Increase in CP at the acetabular base after 6 mm resection (60° of flexion); decrease in CP at the acetabular rim after 6 mm resection (60° of flexion and 20° of extension)	Increase in the CA at the acetabular base after 4 mm resection (60°of flexion); decrease in the CA at the acetabular rim after 6 mm resection (60° of flexion and 20° of extension)	Increase PF at the acetabular base after 6 mm resection (60° of flexion); decrease PF at the acetabular rim after 6 mm resection (60° of flexion and 20° of extension)	Resecting more than 4 to 6 mm of the acetabular rim may dramatically increase CP by 3-fold at the acetabular base
Cadaver/open surgery	Satpathy 2015[29]	Femoral version; effect of femoral retroversion	10 patients; mean age 63 yrs; mean femoral version 18°; no acetabular retroversion	Capsule removed; labrum preserved	Fujifilm Prescale (Low sensitivity 2.5 to 13.5 MPa)	Instron model 1321 and MTS TestStar II controller	Peak stress and peak pressure location	Between the femoral head and acetabulum	1,334 N; joint reaction force rising from or lowering into a chair	Flexion 90° with 0° and 10° of internal rotation	Mean peak CP with no rotation or retroversion 9.3 MPa; combined retroversion and rotation led to localized contact stresses in the anterosuperior region; retroversion increased posteroinferior peak CP; mean peak CP for the combined rotation and retroversion was significantly higher	Displacement of the peak joint CP with femoral retroversion radially outward within the posteroinferior quadrant		Femoral neck retroversion leads to increased hip contact stresses; visible contact of neck onto acetabular rim when it was retroverted, flexed, and internally rotated

BW, body weight; CA, contact area; CP, contact pressure; F, female; FAI, femoroacetabular; LCEA, lateral centre-edge angle; M, male; N/A, not applicable; NR, not reported; PD, pressure distribution; PF, peak force; ROI, region of interest.

0.6 MPa,[27] 9.3 MPa (range 7.2 to 12.2 MPa),[29] and the highest pressures recorded were 5 MPa,[18] 10 MPa,[23] and 9.8 MPa[25] but these measurements were obtained with different loads and different joint positions.

One study reported an extremely low mean CP of 0.1 MPa and used a load of 700 N,[3] and another reported a very low average peak pressure of 0.6 MPa with a load of 350 N.[27]

It should be noted that in the International System of Units the unit for pressure is the pascal (Pa), which is equivalent to one newton per square metre (N/m^2).

Contact area

The contact area increased as the load increased, and the maximum contact area was approximately 14 to 16 cm^2.[21] The maximum contact area occurred with hip extension.[23] With the intact rim, the measured contact area was 8.3 cm^2 at 20° extension and 7 cm^2 at 60° of flexion.[3]

The contact area for the explanted joint was significantly lower in the anterior and posterior regions compared to the intact configuration, where the hip joint was integrated within the whole pelvis.[24]

There was a significant decrease in the contact area after labral resection that improved after reconstruction, although rarely reaching 100% of the native contact area.[4] Surprisingly, Suppauksorn et al[1] found that labral reconstruction had the smallest contact area when compared with the other labral states (native, torn and repaired) using the same loading and joint positions.

Peak force

With an intact acetabular rim, the peak force was 18 N at 20° of extension and 37 N at 60° of flexion.[3] Normalized peak force in three different hip positions did not show differences between labral state (native, torn, repair, and reconstruction).[1] Peak force demonstrated less of an association with the differing labral states (intact, deficient, and reconstructed), probably because peak force is a measurement of a much smaller area.[4]

Effect of the surgery – labrum

One study found no significant increase in the articular pressure after labrectomy or after the removal of the labrum and the transverse ligament. Interestingly, the mean and maximum pressures in the posterior acetabulum decreased significantly.[26]

In contrast, Lee et al[4] found that labral resection resulted in significantly altered biomechanical properties, with large decreases in the contact area and increases in CP. Labral reconstruction with graft significantly improved contact area and CP toward the native state.[4]

In the work by Angsutanasombat et al,[27] labral repair reduced the CP in all conditions except adduction. Additionally, labral reconstruction reduced pressure in the hip socket in all conditions except flexion and internal rotation.

Suppauksorn et al[1] concluded that labral reconstruction resulted in decreased intra-articular contact area and loss of suction seal when compared with labral repair. The study showed a trend to lower pressure and higher contact area in labral repair compared to the labral reconstruction.

Effect of the surgery – bone correction

In an in vivo study, Kaya[28] stated that correction of cam-type deformity prevented the elevation of the hip CP during forceful hip flexion.

In another cadaveric study, Suppauksorn et al[2] concluded that normalized CP in complete cam resection was lower than that of the native cam state as well as partial cam resection.

Bhatia et al[3] studied the effect of sequential rim trimming and found that after 6 mm resection, the CP decreased at the acetabular rim, but resecting more than 4 to 6 mm of the acetabular rim may dramatically generate a three-fold increase in CP at the acetabular base. After a 6 mm acetabular rim resection, the peak force decreased at the rim at 60° of hip flexion and 20° of extension, but at the acetabular base the peak force increased significantly.[3]

Satpathy et al[29] analyzed the effect of femoral retroversion on hip contact stress and concluded that femoral neck retroversion increased hip contact stresses with visible contact of the neck onto the acetabular rim.

Discussion

In this review, we focused on the femoroacetabular CP, CF, and contact area, as abnormal hip biomechanics can predispose to the development and progression of osteoarthritis.[31,32] Most of the studies evaluated the hip contact stress distribution. They assessed different hip conditions such as the labrum status, the biomechanical effect of the cam, the femoral version, the acetabular coverage, and the effect of rim trimming.

Normal morphology

For most of the included studies in this review, the mean CP ranged from 1.54 to 4.4 MN/m^2 or MPa, and the average peak pressures ranged from 2 to 9.3 MPa. This variance may be related to the disparate applied load (100 to 3,600 N), and diverse and few joint positions used in the studies and constraints of different loading apparatus.[33] The measured CP is related to the joint load, but also to the joint position.

von Eisenhart et al[25] recorded the highest CP at midstance, which has a higher load (345% of the BW) compared to heel strike (94% of the BW), but Afoke et al[23] found higher CP with heel strike (3.3 × BW) than at flat foot (1.3 × BW). The load direction relative to the pelvis was also different: at heel-strike it was angled 2° dorsal and 22° medial, at midstance 5° ventral and 11° medial, and at toe-off 7° ventral and 20° medial.[25] The site of the peak local contact stress point was located within 30° of the line of action of the joint load resultant.[20] However, drawing any definitive conclusions regarding the influence of the loading direction on the magnitude of the contact stress is challenging due to variations in the weight of the joint load.

Furthermore, areas of localized peak stresses might be more significant than the average joint CP for cartilage degeneration and longevity. Earlier studies were conducted before the widespread diffusion of descriptions of FAI. Therefore, it is possible that certain hips considered to have a normal morphology could in fact have had a FAI-related deformity that went unrecognized.

Labrum and FAI pathomorphology

Konrath et al[26] found no significant increase in anterior and superior articular pressure after the removal of the labrum in neutral position (intact pelvis). In Lee et al's[4] work, after labral resection (hemipelvis), the CP increased and the contact area decreased significantly at 20° extension and 60° of flexion, but these biomechanical properties improved after labral reconstruction, although differently from the native intact labrum. These differences might reflect that the labral contribution to load bearing may be more important in hip extension and flexion than in a neutral joint position.

The labral status also influences other mechanical properties of the hip joint like the suction seal, articular fluid pressurization, and the joint distraction force.[1,34] In line with these findings, labral preservation and repair, when feasible, is recommended.

The study by Suppauksorn et al[2] analyzed the biomechanical effect of the cam morphology, but did not present absolute values for the parameters, so a comparison with studies where the hips had a normal morphology is not possible.

Complete cam resection decreased the load in the chondrolabral junction and the CP, with a most significant change in the 11 to 2 o'clock region of the acetabulum, which is the most common site for chondral and labral pathology in FAI patients.[2,30,35] Femoral retroversion alters the pattern of impingement, with the contact of the acetabular rim with the anteroinferior femoral neck, which should be considered during surgical planning.[29,36] Nonetheless, there is some concern that cam resection without capsular closure could increase joint microinstability due to the disruption of the labral seal in deep flexion.[37]

The FEA studies showed that cam FAI results in substantially elevated CP,[7,8,10,11] and in a DEA study the peak contact stress normalized after accurate arthroscopic cam correction.[38] These in silico findings are in line with cadaver research and patient outcomes in clinical studies.[35,39]

Compared to the other included studies that present absolute values, Bhatia et al[3] found a lower average mean CP with an intact rim of 0.11 to 0.13 MPa with 20° of hip extension and 60° of hip flexion, respectively. Joint position and load might not explain these differences, but the lateral centre-edge angle (LCEA) of 35.7° with increased acetabular coverage might partially explain the lower CP. Interestingly, this was the only study that presented absolute values for the contact area, CP, and peak force with a Tekscan sensor.

Acetabular rim resection of 6 mm decreased the CP and peak force at the acetabular rim, correcting the impingement, but at the same time dramatically increased the values of these two parameters at the acetabular base.[3] In the FEA model of a severe pincer (protrusio), the acetabular rim trimming increased the medial overload by 28%.[40] The optimal amount of rim trimming should be enough to correct the impingement, but not too much to create instability or increased joint load. A conservative rim resection (postoperative LCEA 34.2° (SD 3.5°)) is also associated with a better clinical outcome compared to a more extensive resection (postoperative LCEA 28.5° (SD 5.3°)).[41,42] These findings should alert surgeons to the biomechanical effects of excessive rim recession.

Sensors

Pressure-sensitive films measure the CP magnitude and distribution between the femoral and acetabular cartilage. The films have different pressure thresholds, and most of the studies used the Fuji film Prescale (low-pressure film 2.5 to 10 MPa). These films have some disadvantages, such as needing to be cut to adapt to the joint morphology, the film thickness can interfere with the joint mechanics, and they produce a static measurement of the highest pressure (peak) recorded at different locations.[33,43]

Flat piezoresistive sensors, like the Tekscan model 5101, allow dynamic CP measurement and pressure distribution mapping, but conform better in joints with a modest curvature. Sensor thickness and wrinkling inside the hip joint can originate artefacts and inconsistencies, and these sensors have a lower spatial resolution compared to the Fuji film Prescale.[43]

There are several limitations in these cadaveric studies: the soft-tissues and capsule excision, which influences joint biomechanics,[44] are necessary to adapt the flat sensor to the hip joint geometry. Furthermore, the intra-articular presence of the sensor may interfere with the joint biomechanics and dynamics, leading to inaccuracies in the data recorded. Other limitations are related to the hip morphology, as the joint curvature affects the sensor's performance, and joint loading also generates shear forces that distort intra-articular sensor output. Furthermore, all cadaver studies used a universal uniaxial testing machine, which does not reproduce the physiological loading kinetics.

Kaya[28] used a fibre optic microtransducer developed for intracranial pressure monitoring to measure the hip CP in hip arthroscopy, but no results were provided. This sensor was used in vivo and allowed dynamic measurement of the CP in anterosuperior femoroacetabular junction in different hip positions. To the best of our knowledge, there is no specific medical device to measure hip CP and force in hip arthroscopic surgery.

Anderson et al[9] compared CP and areas measured using pressure-sensitive film in a cadaveric hip, with the same parameters evaluated by a FEA model created from CT scan of the same cadaver hip. In the cadaver, the average pressure ranged from 4.4 to 5.0 MPa, while FEA predicted an average pressure ranging from 5.1 to 6.2 MPa. The subject-specific FEA model provided a very reasonable prediction of the CP magnitude and contact area when compared directly to pressure film measurements in cadaver.[9]

DEA and FEA models generated from MRI in asymptomatic subjects estimated the peak CP from 2.5 to 12.5 MPa.[12] However, for the hip contact stress due to cam femoroacetabular impingement, Ng et al[11] found elevated CP (median of 10.4 MPa, range 8.5 to 12.2 MPa) in a systematic review of FEA simulations.

These in silico studies and techniques can provide a noninvasive estimation of joint mechanics in vivo, but they present several limitations such as: small sample sizes; exclusion of soft-tissues; ideal joint conditions and oversimplification of joint geometry; the techniques are subject-specific; and the models use adapted material properties for bone and cartilage.[33]

The limitations of this scoping review are mainly related to the heterogeneity of the included studies due to the different studied conditions, testing, and loading settings. Moreover, several studies presented normalized CP and peak force data without reference to the absolute values, preventing comparison with other studies.[1,2,4]

To date, there is no published standardized methodology to access hip contact biomechanics in hip arthroscopy or with the preservation of the periarticular soft-tissues. The mean hip contact pressures in cadaver studies ranged from 1.54 to 4.4 MPa and the average peak pressures ranged from 2 to 9.3 MPa. A tendency towards improved biomechanics (lower CP) was seen with labral repair and reconstruction techniques, as well as with cam correction. Excessive rim recession significantly increased the CP and peak force at the acetabular base. Intraoperative measurement of biomechanical parameters could be used to confirm joint biomechanics restoration.

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