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Appendix

Supplementary Table I. In vitro cadaveric studies on individual capsular ligament contributions, summarizing the study scope, methods, and observations.

STUDY DETAILS		SPECIMENS		METHODS				TAKE-AWAY
Author (year)	**Purpose**	**Sample Size**	**Conditions**	**Measurement**	**Loading**	**Testing Positions**	**Testing Stages**	**Observations**
Martin et al. (2008)[4]	Anatomy and contributions of each capsular ligament (iliofemoral, ischiofemoral, pubofemoral).	n = 12 (Pairs; 6 m, 6 f)	Mean age = 62 y No pathologies.	Motion standardized using an Ilizarov frame and motion tracking. Measured passive hip internal and external rotational range of motion.	No loading recorded.	Tested rotations along neutral swing path at: 10° extension, 0° neutral, 15° flexion, 30° flexion.	- Intact - Resected medial (inferior) iliofemoral ligament - Resected lateral (superior) iliofemoral ligament - Resected pubofemoral ligament - Resected ischiofemoral ligament	- Releasing ischiofemoral ligament increased internal rotation, while releasing pubofemoral ligament increased external rotation, especially during extension. - Releasing medial (inferior) and lateral (superior) iliofemoral ligaments increased external rotation, with lateral (superior) iliofemoral ligament providing more range of motion in flexion and in a neutral position. - Lateral arm release also increased internal rotation, primarily in extension.
Ito et al. (2009)[47]	Contributions of capsule, zona orbicularis, and labrum to hip stability in distraction.	n = 7 (7 m)	Mean age ± SD = 68.5 ± 9.2 y (range, 59-85 y) No pathologies.	Universal tensile tester and custom joint tester, measured distraction force.	Tensile force applied parallel to longitudinal femoral axis, at rate of 0.4 mm/s distraction to 5mm.	Tested distraction force in neutral position of 0° flexion, 0° abduction, 0° internal rotation.	- Intact - Capsule vented - Incised iliofemoral ligament - Circumferentially incised capsule - Partially resected capsule (distal to the zona orbicularis) - Completely resected capsule - Radially incised labrum - Completely resected labrum	- Partially and completely resected capsule phases greatly reduced distraction forces - Proximal-to-middle capsule (including zona orbicularis) acts as locking ring wrapping around femur and neck - Zona orbicularis key for hip stability in distraction.

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Smith et al. (2014)[44]	Role of soft tissue and osseous constraints using robotic testing apparatus.	n = 4 (Pairs from 2 m)	Age = 45 and 81 y No dysplasia or degenerative changes.	Using 6-DOF robotic testing platform, actuated pelvis (from sacroiliac joint) to measure range of motion and translations.	To measure range of motion, applied internal and external rotational torques of 6 Nm and compressive force of 10 N. To measure kinematics, applied 40 Nm in neutral hip position. To measure combine soft and hard tissue forces, applied 40 N, in anterior-posterior, superior-inferior, and medial-lateral in neutral hip position.	Tested range of motion through flexion-extension, abduction-adduction, internal-external rotations.	Note: baseline intact hip was not tested - Capsule vented (1-2 mm hole in capsule) - Capsule separated (separating individual ligaments) - Excised capsule, labrum, ligamentum teres.	- No significant differences in range of motion or kinematic translations between capsule vented and capsule separated conditions. - Bone forces increased in anterior, posterior, and superior directions; while soft tissue forces increased in medial, lateral, inferior directions. - As individual ligaments acted independently of each other to resist motion, recommended soft tissue preservation when possible to maintain normal hip biomechanics.
Myers et al. (2015)[42]	Relative contributions of acetabular labrum and iliofemoral ligament.	n = 15 (From 8 m)	Mean age = 60 y (range, 53-68 y) No pathologies.	Biplane fluoroscopy system measured contributions of labrum and iliofemoral ligament, from internal-external rotations and anterior translation of femur relative to centre of acetabulum.	Applied internal and external torques of 5 Nm, using pulley weights.	Tested rotations in 10° extension, neutral, 10° flexion, and 40° flexion.	- Intact - Resected either iliofemoral ligament or labrum - Rested both - Repair of either - Repair both	- External rotation increased from intact condition to sectioned iliofemoral ligament condition and both-sectioned condition. - No increase in external rotation when labrum-alone sectioned. - No differences between intact and fully repaired conditions. - Ligament-sectioned, both-sectioned, and labrum-repaired conditions all resulted in greater anterior translation than the intact condition.
van Arkel et al. (2015)[46]	Contributions of each capsular ligament (iliofemoral, ischiofemoral, pubofemoral), labrum, ligamentum teres to restraining hip rotation and under joint compression.	n = 9, with 1 hip partially collected due to failure. (All left-sided hips; 6 m, 3 f)	Mean age = 76.4 y (range, 61-89 y) No pathologies.	Servohydraulic tester and custom joint tester, measured rotational restraints of each capsular ligament, ligamentum teres, and labrum in fixed ISB reference frame.	Abduction and adduction measured using pulley weights. Applied internal and external rotational torques of 5 Nm and compressive force of 110 N, using servohydraulic tester.	Tested rotations in abduction, neutral, adduction, during each of sagittal positions in fixed ISB reference frame, from: maximal extension, 0° neutral, 30° flexion, 60° flexion, 90° flexion, maximal flexion.	- Intact - Resected in random order and retested after each (pubofemoral, medial iliofemoral, lateral iliofemoral, ischiofemoral) - Resected ligamentum teres	- Each capsular ligament acted as primary rotational restraint within envelope of motion. - Iliofemoral lateral arm and the ischiofemoral ligaments were primary restraints in testing positions. - Ligamentum teres acted as secondary restraint in high flexion, adduction, and external rotation.
Jo et al. (2018)[20]	Contribution of ligamentum teres	n = 7	Mean age = 55.9 y (range,	Using customized static testing rig	Applied internal and external	For external rotation, tested in neutral, 15°	- Intact.	- Ligamentum teres resection showed no differences during lower torque conditions

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	to intact hip stability.	(4 m, 3 f)	48-69 y) No pathologies.	electromagnetic tracking system, to measure range of motion and femoral head translation.	torques of 2 and 4 Nm. Torque application was 6° varus to anatomical femoral axis.	adduction, 30° abduction during sagittal flexion positions (60°, 90°, 110°). For internal rotation, tested neutral and 15° abduction during sagittal extension positions (-10°, 0°).	- Resected ligamentum teres through cotyloid fossa portal	(2 Nm) nor during internal rotation, in all scenarios. - During higher torque (4Nm), external rotation increased during hip flexion and adducted positions, and deep hip flexion (90°) and abducted positions. - Ligamentum teres resection did not show significant change in internal rotation. - No differences in femoral head translation after resecting ligamentum teres.

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Supplementary Table II. In vitro cadaveric studies on the effects of capsular conditions and surgical stages, summarizing the study scope, methods, and observations.

STUDY DETAILS		**SPECIMENS**		**METHODS**				**TAKE-AWAY**
Author (year)	**Purpose**	**Sample Size**	**Conditions**	**Measurement**	**Loading**	**Testing Positions**	**Testing Stages**	**Observations**
Bayne et al. (2014)[5]	Effect of transverse capsulotomy on rotational and translational hip kinematics.	n = 13 (No details regarding sex)	No details regarding age. Included if centre-edge angle ≤ 25° and Tönnis grade ≤ 1.	Using custom joint tester and optical tracking, measured rotational restraints and translations. (Vented/disrupted acetabular seal with 20-gauge needle between labrum and acetabulum.)	Fixed pelvis and applied 0.588 Nm internal-external torque at truncated femoral diaphysis, using custom joint tester.	Tested rotations in neutral and maximum flexion.	- Intact - Transverse capsulotomy (1 cm from acetabular rim, anterior aspect of femoral neck)	- After capsulotomy, hips rotated more with increased distal, lateral, and anterior femoral head translations in neutral position; and increased medial, posterior, and distal translations in flexion. - Recommended judicious capsular management during arthroscopic hip procedures.
Abrams et al. (2015)[6]	Effect of different interportal and T-shaped capsulotomies on hip rotation	n = 7 (3 m, 4 f)	Mean age = 74 y Included if centre-edge angle 25-40° and intact labrum, cartilage.	Using motion tracking system and servohydraulic tester together with a custom joint tester, measured rotational capsular restraint.	Applied internal and external rotational torques of 10 Nm, using servohydraulic tester tethered to hip assembly. No compressive force noted.	Tested rotation in neutral flexion and 40° flexion.	- Intact - Interportal - Capsulotomy - T-capsulotomy - Repaired capsulotomy - Capsulectomy.	- External rotation increased with T-capsulotomy and capsulectomy compared with intact hip. - Repair restored external rotation to values closer to intact condition.
Jackson et al. (2016)[7]	Effect of simulated instability, capsulotomy on joint mechanics; as well as effect of side-to-side capsular repair, and capsular shift to treat instability.	n = 8 (Pairs; 4 m, 4 f)	Mean age = 58.5 y (range, 48-71 y) No hip pathologies.	Using custom joint tester and 3D digitizing system, measured internal-external rotational motion, maximum extension motion, and distraction distance.	Femur set at 9° adduction with applied compressive force of 20 N, with 10 N on anterior and 10 N on posterior femur. To measure range of motion, applied 1.5 Nm internal-external torque. To measure maximum extension, applied 5 Nm extension torque. To measure femoral distraction, tested	Tested rotational range of motion in 5° extension, 0° neutral, 15° flexion, 30° flexion, and 45° flexion. Femoral distraction tested under 0 N, 40 N, and 80 N of applied load with the femur in 15° of flexion (with no	- Intact - Vented (hole in capsule) - Instability (stretched capsule with 35 Nm extension for 1 hour) - Capsulotomy - Side-to-side repair - Capsular shift	-Instability state increased internal rotation and distraction, compared with intact. - Capsulotomy increased internal and external rotations, distraction, and maximum extension, compared with intact. - Both side-to-side and capsular shift slightly restored internal and external rotations. - Only capsular shift decreased distraction and maximum extension, while side-to-side repair did not. - Suggested that capsular shift can treat hip capsular laxity, by decreasing extension and distraction.

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					under 0 N, 40 N, and 80 N load at 15° hip flexion.	internal-external rotation).		
Wuerz et al. (2016)[8]	Effect of interportal capsulotomy size and repair on external rotation	n = 8 (4 m, 4 f)	Mean age ± SD = 67 ± 23 y Mean BMI ± SD = 21.7 ± 2 kg/m^2 Included if centre-edge angle ≤ 25° and Tönnis grade ≤ 1.	Using motion tracking system and servohydraulic tester together with a custom joint tester, measured external rotational range of motion, hysteresis, neutral zone.	Applied external rotational torques of 6 Nm (0.3 Nm/s), using servohydraulic tester tethered to hip joint assembly. No compressive force noted.	Starting from most internally rotated hip position, tested external rotation in neutral hip position.	- Intact - 4 cm interportal capsulotomy - 6 cm interportal capsulotomy - Repaired capsulotomy	- Larger capsulotomies increased joint mobility. - No clear differences between 4 and 6 cm capsulotomy. - Complete capsular closure restored these measures compared with intact condition.
Khair et al. (2017)[10]	Effect of interportal capsulotomy size on hip distraction force. Compare simple side-to-side suture with acetabular-based anchors for capsular repair techniques.	n = 12 (7 m, 5 f)	Mean age ± SD = 65.67 ± 9.77 y Mean BMI ± SD = 29.06 ± 6.94 kg/m^2 Centre-edge angle >25°. Excluded if joint space < 2 mm or Tönnis grade >2. No other hip pathologies.	Using universal tensile testing system together with a custom joint tester, measured restraining force of capsule and subsequently repair during distraction.	Applied 6 mm distraction using tensile tester.	Tested in slack region of capsular tissue properties.	- Intact - 2 cm capsulotomy - 4 cm capsulotomy - 6 cm capsulotomy - 8 cm capsulotomy - 6 hips underwent simple suture repairs and 6 hips underwent suture anchor repairs	- Larger capsulotomies resulted in less force to distract hip. - Although capsular repair with either simple sutures or suture anchors restored distractive stability to intact state, side-to-side suture repair was better to restore distraction force compared with suture anchor repair.
Philippon et al. (2017)[11]	Effects of several capsular management conditions using a robotic testing platform (Goldsmith)	n = 10 (10 m)	Mean age = 51.3 y (range, 38-65 y) Mean BMI = 31.3 k/m2 (range, 19.7-38.6 kg/m^2) No history of injury or surgery. No information on pathologies.	Using 6-DOF robotic testing platform, actuated femur to measure range of motion.	Applied internal-external rotational and abduction-adduction torques of 5 Nm and compressive force of 10 N, using robot.	Tested rotations sagittal positions, from: extension 10°, 0° neutral, 15° flexion, 30° flexion, 60° flexion, 90° flexion.	- Intact - Portal incisions - Interportal capsulotomy - Interportal capsulotomy repair - T-capsulotomy - T-capsulotomy repair - Large capsular defect - Capsular reconstruction	- All capsulotomy procedures (portals, interportal capsulotomy, T-capsulotomy) increased in external, internal, adduction, abduction rotations compared with intact state throughout. - Reconstruction reduced rotation compared with large capsular defect state for internal-external rotation at higher risk hip flexion positions. - Repair of interportal and T-capsulotomy reduced rotational motion, compared with respective unrepaired conditions. - Reconstruction also substantially reduced abduction-adduction rotations.
Hebert et al. (2017)[9]	Effect of effusion (simulating multiple portals) and capsular tear on hip transverse plane motion.	n = 10 (Pairs; no details regarding sex)	Age = 28-82 y No details on pathologies or inclusion/exclusion criteria.	Using custom joint tester, measured internal-external rotational motion.	Femur set at 5° valgus for neutral position. Applied internal and external rotational torques of 1.5 Nm and	Tested rotational range of motion at 0° neutral and 90° flexion.	- Intact - Effusion (10 ml saline infusion) - Capsular tear (stab incision across superior capsule)	- Effusion decreased rotational range of motion throughout, with greater effect on external rotation at 0° flexion. - Capsular tear increased internal and external rotation in 0° neutral; and increased internal rotation in 90° flexion.

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			(Post-hoc showed some osteoarthritis from fluoroscans.)		compressive force of 30 N, using custom joint tester.			
Han et al. (2018)[13]	Relationship between capsular laxity and abnormal hip rotation and translation.	n = 8 (6 m, 2 f)	Mean age = 46 y (range, 23-79 y) No hip pathologies.	Using custom joint tester and optical tracking, measured rotational restraints and translations. Devised microinstability index (assembled path of motion during internal and external).	Applied 190 N through lumbar spine. Applied 5 Nm internal-external torque at truncated femoral diaphysis, using custom joint tester.	Tested rotations in full extension, neutral 0°, 30° flexion, 60° flexion, and 90° flexion.	- Intact - Capsular modification (~30 pie-crusting using scalpel stab incisions to capsule) to simulate capsular defect and joint laxity	- Intact hip rotated concentrically only within 30° flexion. - Capsular modification increased internal-external rotation and femoral head translations; displaying the femoral head inferiorly during external rotation and anteroinferiorly during internal rotation. - Capsular laxity leads to microinstability of the hip, but there was no correlation between rotational laxity and the increase in femoral head translation.
Weber et al. (2018)[14]	Effects of increasing interportal capsulotomy size, conversion to T-capsulotomy, subsequent repairs	n = 8 (8 m; 3 right, 5 left)	Mean age ± SD = 63.3 ± 4.0 y Mean BMI ± SD = 29.7 ± 4.0 kg/m^2 Included if lateral center-edge angle > 25°, and Tönnis 0-1. Excluded if severe joint deformity, advanced osteoarthritis, prior surgery, previous hardware placement, or previous fractures.	Using universal tensile testing system together with a custom joint tester, measured restraining force of capsule and subsequently repair during distraction.	Applied 6 mm distraction using tensile tester.	Tested in slack region of capsular tissue properties.	- Intact - 2 cm capsulotomy - 4 cm capsulotomy - half-T with 2 cm vertical capsulotomy - full-T with 4 cm vertical capsulotomy - Repair vertical limb portal - Repair full	- Largest force decrease between intact hip and 2 cm interportal capsulotomy. - Increasing interportal capsulotomy (2 to 4 cm) required less force to distract. - No difference between 4 cm interportal with half-T and full-T capsulotomies. - Isolated T-limb repair partially restored stability while complete repair exceeded native values.
Fagotti et al. (2018)[12]	Effects of capsular reconstruction with iliotibial band allograft on distraction	n = 8 (No details regarding sex)	Mean age = 53.4 y (range, 42-59 y) Mean BMI = 25.3 kg/m^2 (range, 18.5-30.6 kg/m^2) No pathologies or surgeries.	Using dynamic tensile testing system, measured distraction force of labrum and capsule as well as subsequent repair (using iliotibial band graft).	Pre-conditioned by applying compressive loads of 20 and 500 N. Applied 6 mm distraction (rate 0.5 mm/s) using tensile tester.	Tested in neutralized position.	- Intact - Performed both in random order, with either capsular defect (20 30 mm defect) or capsular reconstruction (iliotibial allograft, folded twice over)	- Distraction force for capsular reconstruction was greater than capsular defect state; and not different from that intact state. - Found steep “first peak” that resisted much of distraction force. - Distinguished two phases in distraction process, with first phase characterizing effect of labral seal. - Allograft increased distractive stability and can be effective option for capsular deficiency.

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Johannsen et al. (2019)[69]	Role of capsular laxity in hip microinstability	n = 7 (5 m, 2 f)	Mean age = 31 ± 11 y (range, 18-46 y) No hip pathologies	Using dynamic tensile testing system together with a custom joint tester and motion tracking system, measured internal-external rotation and femoral head displacement in neutral and biomechanical positions.	Using alignment apparatus, aligned hip to neutral position. For rotational range of motion, applied internal-external rotations of 5 Nm. For anterior-posterior, medial-lateral, superior-inferior translation, applied force of 50 N in each planar directions using universal tester and springs. Applied compressive force of 10 N, using universal tester.	Tested in neutral and hyperextension: internal-external rotations, medial-lateral translation	- Intact - Capsular venting (18-gauge needle under 100 N distraction and 50 N lateral loading) - Capsular stretching (maximal extension and external rotation)	- In anatomic neutral alignment, cyclic stretching of anterior hip capsule increased hip rotation. - Stretching of anterior hip capsule increased displacement in all three planes relative to vented state. - Anterior capsule controls rotation and displacement.
Baha *et al.* (2019)[49]	Effect of capsulotomy and repair techniques on frontal and sagittal hip kinematics	n = 8 (6 m, 2 f)	Mean age = 78.3 ± 6.0 y No hip pathologies	Using custom joint tester and optical tracking, measured rotational restraints.	Applied manual compressive force of 10 N. Applied manual rotational torque of 3 Nm.	Tested in sagittal angles: 15° extension, 0° neutral, 30° flexion, 60° flexion, and 90° flexion. At each sagittal angle, tested in: neutral, maximum abduction, maximum adduction.	- Intact - 2 portal placements - Interportal capsulotomy - Interportal capsulotomy repair - T-capsulotomy - T-capsulotomy partial repair - T-capsulotomy full repair	- T-capsulotomy increased range of motion compared with intact. - Complete capsular repair after interportal or T-capsulotomy restored range of motion and joint translation to intact values.

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Supplementary Table III. In vitro cadaveric studies on hip preservation and arthroplasty surgery, summarizing the study scope, methods, and observations.

STUDY DETAILS		**SPECIMENS**		**METHODS**				**TAKE-AWAY**
Author (year)	**Purpose**	**Sample Size**	**Conditions**	**Measurement**	**Loading**	**Testing Positions**	**Testing Stages**	**Observations**
van Arkel et al. (2018)[70]	Effects of total hip implant head sizes and neck lengths on capsular ligament function.	n = 8 (5 m, 3 f)	Mean age = 64 y (range, 48-82 y) No hip pathologies.	Using servohydraulic tester and custom joint tester, measured rotational restraints of capsule, in fixed ISB reference frame.	Applied abduction and adduction torques of 5 Nm, using pulley weights. Applied internal and external rotational torques of 5 Nm and compressive force of 10 N, using servohydraulic tester.	Tested rotations in full extension with full abduction, neutral, 30° flexion, 90° flexion, and full flexion with full adduction.	- Intact - Varying implant head sizes (28, 32, 36 mm) with varying neck lengths (0, 5 mm, 10 mm offset); and retested after each combination Note: implant assembly inserted through cotyloid fossa portal (leaving capsule fully intact).	- Internal-external rotation increased following THA, indicating late engagement of capsule and reduced function; where internal rotation was affected more than external. - Increasing neck length reduced hypermobility, while too much lengthening restricted external rotation; whereas larger head sizes slightly reduced hypermobility.
Ng et al. (2018)[15]	Individual contributions of surgical capsulotomy, cam resection, and capsular repair on passive range of motion and torque.	n = 12 (Pairs, 6 m)	Mean age = 45 ± 9 y Mean BMI = 24 ± 3 kg/m2 Included if male, age < 60 y, BMI < 30 kg/m2, showed cam deformity. No other hip pathologies.	Using 6-DOF robotic testing platform and optical tracking system, actuated femur to rotate and recorded intact hip's neutral path of rotational motion. (Recorded intact hip's motion used to replay motion for subsequent testing stages.)	Applied 5 Nm internal-external torques and abduction-adduction; and compressive force of 5 N, using robotic testing platform.	Tested rotations in full extension, 0° neutral, 30° flexion, 90° flexion, flexion-adduction and internal rotation (FADIR), flexion-abduction and external rotation (FABER).	For range of motion - Intact - T-capsulotomy - Cam resection - Capsular repair For changes in torque, replayed motion of Intact condition after: - T-capsulotomy - Cam resection	- For changes in range of motion, external rotation increased after capsulotomy, but internal rotation only increased at flexion 90° and FADIR after cam resections. - Capsular repair restrained external rotation compared with capsulotomy stage. - For changes in torque, internal-external torque decreased after capsulotomy. - Cam resection further reduced internal torque resistance during flexion 90° and FADIR; where cam deformity accounted for 21-27% of torsional resistance in deep flexion. - Resecting cam deformity would remove loading (21-27%) on chondrolabral junction.
Logishetty et al. (2019)[75]	Effects of hip resurfacing arthroplasty, dual mobility hip arthroplasty, and total hip arthroplasty on capsular ligament function; as well as anterior and posterior surgical approach.	n = 16 (Pairs; 5 m, 3 f)	Mean age = 57 y (range, 31-67 y) No hip pathologies.	Using servohydraulic tester and custom joint tester, measured rotational restraints of capsule, in fixed ISB reference frame.	Applied abduction and adduction torques of 5 Nm, using pulley weights. Applied internal and external rotational torques of 5 Nm and compressive force of 110 N, using servohydraulic tester.	Tested rotations in full extension with full abduction, neutral, 30° flexion, 90° flexion, and full flexion with full adduction.	- Intact Note: left-sided hips (n = 8) tested with anterior approach; right-side hips (n = 8) tested with posterior approach. - Hip resurfacing arthroplasty (matching native head size) - Randomized either dual mobility	- Hip resurfacing provided near native internal-external rotation; while dual mobility arthroplasty slightly increased range of motion, and total hip arthroplasty further increased range of motion (where capsular function is lost). - In low flexion and extension positions, posterior capsulotomy provided more normal function as it was shortened during posterior repair. - Posterior approach had higher dislocation risks in deep flexion. - In deep flexion positions, anterior capsulotomy functioned better, as there

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							arthroplasty (22-28 mm head size) or total hip arthroplasty (32 mm head size); and retest with other - Capsular repair	were no dislocations. - Suggested native head-size and capsular repair preserves capsular function after arthroplasty.

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