Contributions of the Abductor Muscles to Rotational and Distractive Stability of the Hip in a Biomechanical Cadaveric Model

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Background: The gluteus minimus (GMin) and gluteus medius (GMed) are important dynamic stabilizers of the hip, but quantitative data on their biomechanical roles in stabilizing the hip are currently lacking.

Purpose: To (1) establish a reproducible biomechanical cadaveric model of the hip abductor complex and (2) characterize the effects of loading the GMin and GMed on extraneous femoral rotation and distraction.

Study Design: Controlled laboratory study.

Methods: A total of 10 hemipelvises were tested in 4 muscle loading states: (1) unloaded, (2) the GMin loaded, (3) the GMed loaded, and (4) both the GMin and GMed loaded. Muscle loads were applied via cables, pulleys, and weights attached to the tendons to replicate the anatomic lines of action. Specimens were tested under internal rotation; external rotation; and axial traction forces at 0°, 15°, 30°, 60°, and 90° of hip flexion.

Results: When loaded together, the GMin and GMed reduced internal rotation motion at all hip flexion angles ($P < .05$) except 60° and reduced external rotation motion at all hip flexion angles ($P < .05$) except 0°. Likewise, when both the GMin and GMed were loaded, femoral distraction was decreased at all angles of hip flexion ($P < .05$).

Conclusion: The results of this study demonstrated that the GMin and GMed provide stability against rotational torques and distractive forces and that the amount of contribution depends on the degree of hip flexion.

Clinical Relevance: Improved understanding of the roles of the GMin and GMed in preventing rotational and distractive instability of the hip will better guide treatment of hip pathologies and optimize nonoperative and operative therapies.

Keywords: hip abductor muscles; hip biomechanics; hip microinstability; gluteus medius; gluteus minimus

The hip abductor complex, comprising the gluteus minimis (GMin) and gluteus medius (GMed), is sometimes referred to as the rotator cuff of the hip because of its ability to stabilize the femoral head center during hip range of motion. The GMin and GMed have critical roles for normal hip function as evidenced by their pathologies. For instance, abductor tendon tears and muscular deficiencies result in Trendelenburg gait and are associated with hip pain, weakness, and functional disability.[5,11]

Furthermore, interventions that effectively correct pathologies of the hip abductors relieve symptoms and restore function. For example, repair of abductor tendon tears has been shown to improve pain, strength, gait, and patient-reported outcomes.[8] Moreover, optimizing the function of the hip abductors through nonoperative methods is the first-line treatment for conditions such as femoroacetabular impingement (FAI) and trochanteric bursitis.[16,17,20] Abductor muscle strengthening has also been suggested as a treatment option for the emerging concept of hip microinstability, with the rationale being that it is analogous to concavity compression produced by the rotator cuff in the shoulder. Similarly, optimizing the muscular envelope of the hip may improve dynamic

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stabilization in settings of borderline hip dysplasia and iatrogenic hip instability secondary to surgical capsulotomy.

Many factors contribute to hip stability. Static stabilizers include the osseous ball-and-socket morphology, capsuloligamentous structures (ie, iliofemoral, ischiofemoral, and pubofemoral ligaments), zona orbicularis, ligamentum teres, and synovial fluid suction seal generated by the femoral head, labrum, and transverse acetabular ligament.[7,13,23] Dynamic stabilizers are the muscles that span the hip to provide compression of the femoral head into the pelvic acetabulum.[22] Currently, the specific role of each muscle on hip stabilization in terms of quantitative contribution has not been thoroughly investigated.

The goals of this study were to (1) establish a reproducible biomechanical cadaveric model of the hip abductor complex and (2) characterize the roles of the GMin and GMed in stabilizing the hip against undue femoral rotation and distraction. Based on anatomic footprints and trajectories of pull, we hypothesized that the GMin and GMed function in part to stabilize the hip against rotational torques and distractive forces as a function of hip flexion with the pelvis in neutral stance such as during gait. In addition to better understanding the role of the hip abductor complex in joint stabilization, the clinical significance of this work lies in its potential to enhance therapies that address pathologies related to hip instability.

METHODS

Specimen Preparation

Institutional review board approval was not required for this laboratory investigation using deidentified cadaveric specimens. A total of 10 fresh-frozen hemipelvises were procured from an institution-approved tissue bank with an average age of 44 ± 5.9 years (range, 32-50 years) from 3 female and 7 male donors. Inclusion criteria for cadaveric specimens were no gross deformity, no history of hip surgery, and age $\leq$50 years. Specimens were stored at -30°C and thawed at room temperature for 48 hours before preparation.

Hemipelvis specimens were prepared as follows (Figure 1): all soft tissues were sharply removed except for the hip capsule and distal insertions of the GMin and GMed tendons. Both osseous and capsular insertions of the GMin were preserved. Running locking nonabsorbable sutures were placed in the preserved GMin and GMed tendinous attachments to the greater trochanter for installation to a weighted pulley system (No. 2 FiberWire; Arthrex). Eyelet screws were placed in the outer table of the ilium to estimate the area average of the tendinous origins of the GMin and GMed to simulate the anatomic force vectors based on previous studies.[10,11] Osseous landmarks were referenced instead of actual tendons to minimize variability due to irregular cross-sections of the tendinous footprints and to improve standardization. The line of action of each muscle was further determined by eyelet height relative to the surface of the bone, which was approximated by positioning the eyelets on the curvilinear plane shared by the iliac crest and greater trochanter.

More specifically, to simulate the GMed, 2 eyelet screws were used to estimate its broad anterior to posterior fan-shaped origin on the gluteal fossa of the ilium. Placement was determined by finding the midpoint between the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). From this midpoint, a line perpendicular to the axis of the ASIS and PSIS was drawn to the iliac crest. One eyelet screw was placed at the midpoint between the middle of the drawn line and the ASIS, and the second eyelet screw was placed at the midpoint between the middle of the drawn line and the PSIS (Figure 1A). For simulation of the GMin, a single eyelet screw was used to estimate the narrower anterior to posterior origin on the gluteal fossa of the ilium. The midpoint between the anterior inferior iliac spine (AIIS) and the apex of the greater sciatic notch was identified. A perpendicular line starting from this midpoint was then drawn to the anterior/middle gluteal line. The eyelet screw was placed at the midpoint of this line (Figure 1A).

Biomechanical Testing

Each hemipelvis was secured to a metal plate on a multiaxial hip jig and fixed in a neutral stance as described by Morosato et al[18] such that the anterior pelvic plane, defined by the ASIS and pubic tubercle, was vertically oriented (Figure 1B). The femur was sectioned 9 cm from the inferior aspect of the lesser trochanter and oriented with respect to the hemipelvis in neutral rotation and abduction, where the linea aspera was directed posterior and the anatomic axis of the femur was positioned along the vertical in the coronal plane (Figure 1C).[25] The distal aspect of the femur was potted in an aluminum cup fitted

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Ethical approval was not sought for the present study.

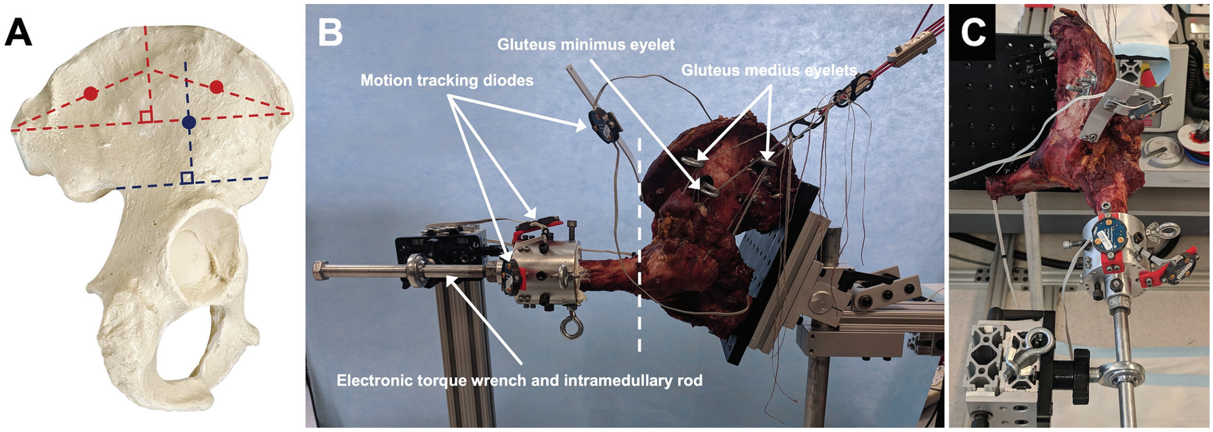

Figure 1. (A) Eyelet screw placement for the GMin (blue circle) and GMed (red circles) in a right hemipelvis. The transverse red dotted line goes from ASIS to PSIS and transverse blue dotted line goes from AIIS to apex of greater sciatic notch. The vertical red dotted line is perpendicular to and bisects the transverse red dotted line. The vertical blue dotted line is perpendicular to and bisects the transverse blue dotted line and goes to the anterior/middle gluteal line, which separates the origins of the GMin inferiorly and GMed superiorly. Oblique red dotted lines go from middle of the vertical red dotted line to the ASIS and PSIS. The middle of the oblique red dotted lines and the vertical blue dotted line are the locations for the islet screws. Setup for biomechanical testing of a left hemipelvis from (B) side and (C) frontal views. The hemipelvis is secured to a multiaxial jig and oriented in neutral pelvic stance with the anterior pelvic plane oriented along the vertical (white dotted line). The hip is flexed at 90° in this example; 2 motion tracking diodes are placed on the femoral pot and 1 is placed on the iliac crest. Eyelet screws are used to guide muscle loads along the estimated trajectories of the GMin and GMed force vectors. AIIS, anterior inferior iliac spine; GMed, gluteus medius; GMin, gluteus minimus; PSIS, posterior superior iliac spine.

with an intermedullary rod to allow for load application. Weights of 10 and 20 pounds (4.5 and 9 kg) were applied via cables connected to the sutures using S-shaped carabiners and directed through the eyelet screws to simulate loading of the GMin and GMed, respectively. These loads were chosen based on the stance phase of the gait cycle as determined by an electromyogram-to-force model that approximated hip gait force generated by the GMed to be between 0 N and 390 N, as well as the relative cross-sectional areas of each muscle.[3] Maintaining the GMin and GMed within this physiological force range prevents abnormal shifts of the femoral head center but was not intended to accurately simulate abductor muscle function with respect to changes in hip flexion during gait. Motion-tracking diodes (Optotrak Certus; NDI) were placed on the iliac crest and femoral pot to track the position of the femur with respect to the hemipelvis using a floating coordinate system akin to the International Society of Biomechanics Joint Coordinate System for motion of the hip joint.[26]

For biomechanical testing of rotational stability, the femur of each specimen was statically loaded with an electronic torque wrench (model J6342; Proto Industrial Tools; calibrated accuracy of ±1%) to produce 5 N·m of internal rotation torque or 5 N·m of external rotation torque. For distractive stability testing, a distraction force of 0 N to 150 N was applied in 5-N increments along the long axis of the femur while hip abduction/adduction and flexion/extension were maintained in neutral and recorded with an S-beam load cell (LCCA-100; OMEGA Engineering). All torques and forces were assumed to represent those acting across the hip joint. Each specimen was sequentially tested at 0°, 15°, 30°, 60°, and 90° of hip flexion and allowed to equilibrate in each of the 4 muscle states: (1) unloaded, (2) the GMin loaded, (3) the GMed loaded, and (4) both the GMin and GMed loaded. It should be noted that, even with no simulated muscle loading, there was resistance against hip rotation and distraction provided by the stabilizing properties of the osseous and capsuloligamentous structures. Longitudinal displacement and axial rotation measurements of the femur relative to the hemipelvis were recorded using a motion tracking system (Optotrak Certus; NDI; 0.1 mm accuracy and 0.01 mm resolution).

Data Analysis

A multivariate mixed repeated-measures model was used to determine the effect of each muscle loading state, hip flexion angle, rotational torque, and axial distractive force on hip kinematics (SAS Version 9.4; SAS Institute). The Tukey-Kramer procedure was used to correct for multiple comparisons. Statistical significance was set at $P < .05$.

RESULTS

Internal Rotation

Unloaded specimens subjected to 5 N·m of internal rotation torque at 0° of hip flexion demonstrated a mean 33.5° ± 14.9° of femoral internal rotation (Figure 2). Hip internal rotation decreased by 2.9° ($P < .001$), 8.0° ($P < .001$), and 12.3° ($P < .001$) with simulated loading of the GMin,

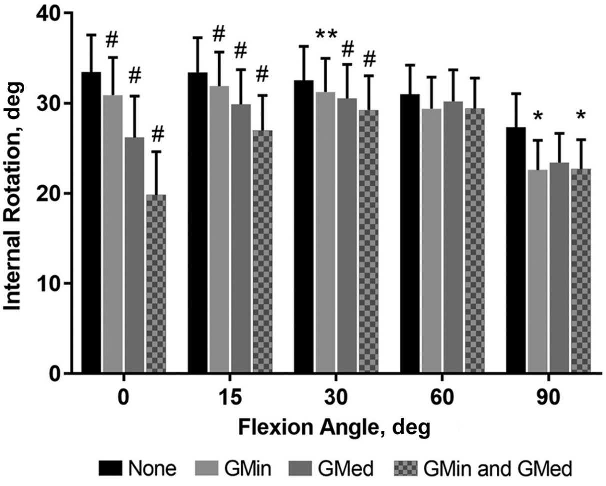

Figure 2. Mean internal rotation of the femur as a function of hip flexion at 0°, 15°, 30°, 60°, or 90° and with no load (None), only the GMin loaded, only the GMed loaded, or both the GMin and GMed loaded. Error bars indicate standard deviation. Statistically significant difference from hip rotation when no load is applied: **P* < .05, ***P* < .01, #*P* < .001. GMed, gluteus medius; GMin, gluteus minimus.

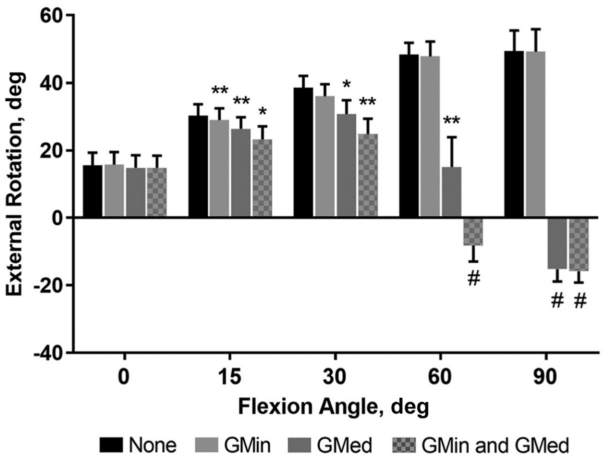

Figure 3. Mean external rotation of the femur as a function of hip flexion at 0°, 15°, 30°, 60°, or 90° and with no load (None), only the GMin loaded, only the GMed loaded, or both the GMin and GMed loaded. Error bars indicate standard deviation. Negative values indicate internal rotation of the femur. Statistically significant difference from hip rotation when no load is applied: **P* < .05, ***P* < .01, #*P* < .001. GMed, gluteus medius; GMin, gluteus minimus.

GMed, and both hip abductors, respectively. Simulated hip abductor loading similarly showed decreased internal rotation with 5 N·m of internal rotation torque at both 15° (*P* < .05) and 30° (*P* < .05) of hip flexion as compared with the unloaded state. A trend toward decreased internal rotation at 60° of hip flexion was also observed, but statistical significance was not reached (*P* = .26). When positioned at 90° of hip flexion, specimens had an average of 27.3° ± 13.5° of femoral internal rotation in the unloaded state. Femoral internal rotation decreased by 4.7° (*P* < .05), 3.7° (*P* > .05), and 4.6° (*P* < .05) when the GMin, GMed, and simultaneous abductor loading were applied, respectively.

External Rotation

Loading of the hip abductors did not significantly reduce femoral external rotation when an external torque of 5 N·m was applied to hips in 0° of flexion (*P* > .05) (Figure 3). The GMin alone reduced femoral external rotation by 1.3° (*P* < .01) in 15° of hip flexion, but did not contribute significantly to rotational stability at 30°, 60°, or 90° of hip flexion (*P* > .05 each). The GMed alone provided increased rotational stability as hip flexion increased, reducing external rotation by 3.9°, 7.8°, and 33.2° at 15°, 30°, and 60 ° of hip flexion, respectively (*P* < .05 each). At 90° of hip flexion, the GMed produced an internal rotation force that overpowered the 5 N·m external rotation torque, internally rotating the femur to 15.2° (*P* < .0001). When both the GMin and GMed were loaded, results were similar to the GMed alone, demonstrating decreased external rotation under a 5 N·m external torque compared with the unloaded state at 15° and 30° of hip flexion (*P* < .05 each), and placing the femur into 8.2° and 15.8° of internal rotation at 60° and 90° of hip flexion, respectively (*P* < .0001 each).

Femoral Distraction

In the presence of a femoral axial distractive force at 0° of hip flexion, the GMin decreased hip distraction significantly when the applied distraction force was >50 N (*P* < .05), and both the GMed and simultaneous gluteal loading significantly decreased hip distraction when the applied force was >45 N (*P* < .05) (Figure 4). At 15° of hip flexion, the GMin loaded specimens showed significantly less distraction than unloaded specimens from 5 to 85 N (*P* < .05), but the effect was no longer significant when forces increased above 85 N (*P* > .05). The GMed and simultaneous gluteal loaded specimens at 15° of hip flexion showed significantly decreased hip distraction at all tested forces (*P* < .05). At 30° of hip flexion, the GMin loading was similarly effective at decreasing hip distraction up to 70 N (*P* < .05), but did not significantly resist distraction compared with the unloaded state for forces >70 N (*P* > .05). The GMed and simultaneously loaded abductor states both decreased distraction across the hip from 0 N to 150 N at 30° of hip flexion, although loading both abductors together provided significantly less distraction than GMed alone when the distractive force was ≥125 N (*P* < .05). At 60° of hip flexion, GMin loading decreased hip distraction significantly from 20 N to 75 N (*P* < .05) and above 135 N (*P* < .05). Both the GMed and simultaneous abductor loading states provided significantly

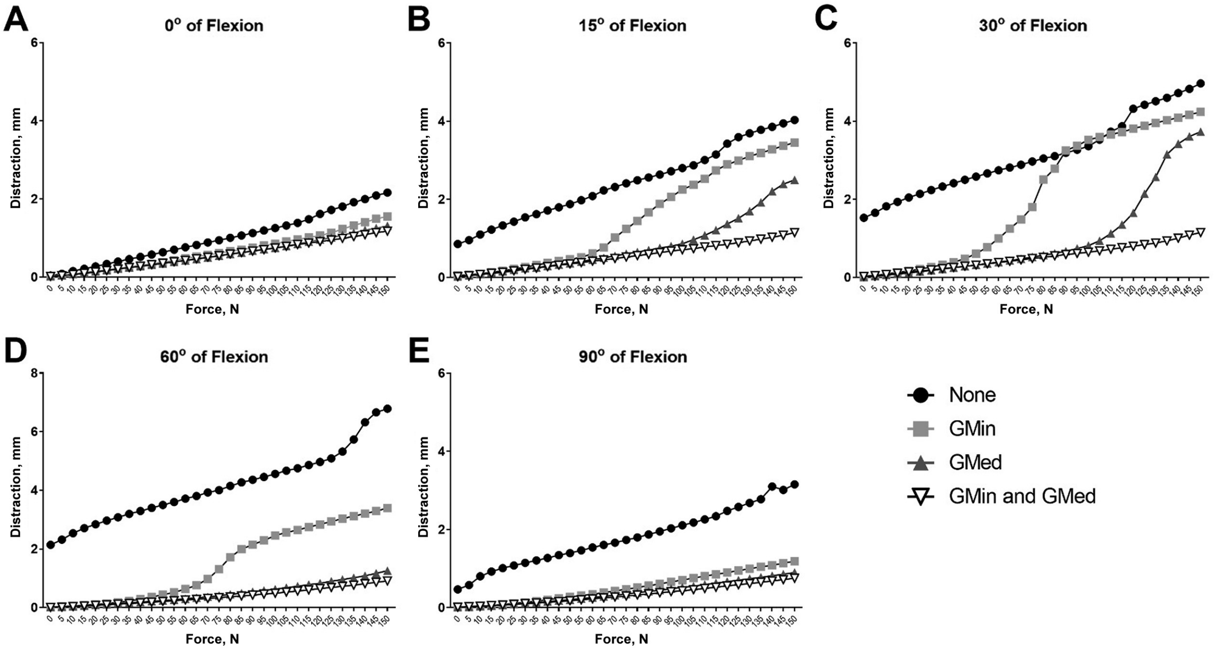

Figure 4. Hip distraction as a function of distractive force, hip flexion angle at (A) 0°, (B) 15°, (C) 30°, (D) 60°, and (E) 90°, and muscle loading state with no load (None), only the GMin loaded, only the GMed loaded, or both the GMin and GMed loaded. GMed, gluteus medius; GMin, gluteus minimus.

reduced distraction against 15 N to 150 N of force compared with the unloaded specimens ($P < .05$). There was no significant difference between any of the muscle states (GMed, GMin, or GMin and GMed) when the hip was at 60° of flexion. At 90° of hip flexion, all 3 muscles states significantly decreased hip distraction from 0 N to 150 N ($P < .01$), although simultaneously loaded specimens showed significantly less distraction than GMin loading alone when the distractive force was ≥115 N ($P < .05$). All results are summarized in Figure 5.

DISCUSSION

The hip abductors can be a substantial source of pathology leading to pain, weakness, gait disturbance, and physical disability. Despite general agreement that the hip abductors are important for hip function, there is little quantitative data to demonstrate the specific contributions of the GMin and GMed to hip stability. This biomechanical cadaveric study analyzed the effects of loading the GMin and GMed, individually and simultaneously, on rotational and distractive stability of the hip. The main findings were that both the GMin and GMed stabilize the hip against rotational torques and distractive forces and that their relative contributions are dependent on the position of hip flexion. Although previous studies have utilized cadaveric specimens to study biomechanics of the hip, only a few have focused on the roles of the GMin and GMed in native hips.[12,14]

The hip abductors provided stability against internal rotation torque at all hip flexion angles except 60°. Contributions to stability against internal rotation at 90° of hip flexion is of particular interest, because FAI is often symptomatic in high degrees of flexion and internal rotation.[6,19] Our results are consistent with other clinical studies that support the efficacy of nonoperative treatment for FAI with abductor strengthening, providing biomechanical evidence for abductor strengthening as a first-line treatment for FAI.[17,20] Specifically, the hip abductors have the potential to resist pathologic positions of internal rotation that are symptomatic in FAI. The GMin provided the greatest contribution to stability against internal rotation at 90° of hip flexion. This finding may be related to the distal insertion of the GMin positioned on the anterior facet of the greater trochanter. In addition, the distal attachments of the GMin to the hip capsule may contribute to stability as it is possible that capsular tension changes when the GMin is loaded.[1,10,11]

Hip stability against external rotation torque was observed with hip abductor loading at all hip flexion angles except 0°. At higher hip flexion angles, resistance to external rotation was significant only when the GMed was loaded (i.e., only the GMed loaded, both the GMed and GMin loaded). The line of action of the GMed based on the anatomic location of its distal insertion may offer an explanation. By inserting on the lateral facet of the greater trochanter, the trajectory of pull of the GMed is more posterior in relation to that of the GMin,[10,11,21] which is more advantageous to produce a stabilizing internal rotation torque. Resistance to external rotation at 0° of hip flexion is of

		0°	15°	30°	60°	90°
Internal Rotation Torque (5 N·m)	GMin	+	+	+	ns	+
	GMed	+	+	+	ns	ns
	GMin + GMed	+	+	+	ns	+
External Rotation Torque (5 N·m)	GMin	ns	+	ns	ns	ns
	GMed	ns	+	+	+	++
	GMin + GMed	ns	+	+	++	++
Distraction Force (0-150 N)	GMin	+ (> 50N)	+ (5-85N)	+ (< 70N)	+ (20-75N, >135N)	+ (0-150N)
	GMed	+ (> 45N)	+ (0-150N)	+ (0-150N)	+ (15-150N)	+ (0-150N)
	GMin + GMed	+ (> 45N)	+ (0-150N)	+ (0-150N)	+ (15-150N)	+ (0-150N)

Figure 5. Overview of the GMin and GMed stability against internal rotation torque, external rotation torque, and distraction force at 0°, 15°, 30°, 60°, and 90° of hip flexion. +, provided stability; ++, overpowered applied rotational torque; ns, no significant contribution to stability. GMed, gluteus medius; GMin, gluteus minimus.

clinical relevance because of the relationship between anterior capsular insufficiency and symptomatic hip instability. Anterior capsule insufficiency symptoms are typically reproduced in a position of hip extension and external rotation.[4,22] Since the hip abductors did not contribute to external rotation stability at 0° of hip flexion, therapies that strengthen the hip abductors may not be effective in treating anterior capsule insufficiency from a biomechanical standpoint.

The hip abductor muscles resisted distractive forces at all tested angles of hip flexion. This finding is applicable to microinstability of the hip, a condition related to anatomic, traumatic, or iatrogenic etiologies, and characterized by nonspecific deep groin pain and apprehension or giving way with certain activities such as those involving hip external rotation and extension. Clinically, reproducible symptoms with distractive testing maneuvers can suggest hip microinstability.[4,22] Furthermore, a recent biomechanical investigation of microinstability of the hip found that displacement is a measure of stability.[14] Hence, based on the results of this study, abductor strengthening has therapeutic potential to mitigate distractive hip microinstability.

The finding that the hip abductors provide both internal and external rotation stability based on degree of hip flexion is supported by literature. Delp et al[9] demonstrated in a cadaveric model that the rotational moment arm of the GMed changes with hip flexion. At 0° of hip flexion, the anterior compartment of the GMed has a small internal rotation moment arm, while the middle and posterior compartments of the GMed have external rotation moment arms. As the hip is flexed to 90°, the internal rotation moment arm of the anterior compartment increases, and the moment arms of the other compartments switch from external to internal. Similarly for the GMin, the posterior compartment has an external rotation moment arm at 0° of hip flexion, but has an internal rotation moment arm at 90° of hip flexion.[9] Furthermore, several authors have shown in clinical studies that isokinetic hip internal rotation strength is greater in flexion compared with extension, which may be attributed to changes in muscle length and/or moment arm at varying hip positions.[2,15] The present study adds to the literature with quantitative data showing that the GMed not only resists external rotation torque, particularly when hip flexion is at 60° or more and becoming an internal rotator at 90° of hip flexion (Figure 3), but that it also resists internal rotation torque with hip positions between 0° and 30° (Figure 2). The GMin similarly resists rotational torque but to a lesser degree and resists internal rotation torque only when deviating away from 60° of hip flexion and external rotation torque at 15° of hip flexion (Figures 2 and 3).

It is important to note that this study did not isolate contributions of the abductor muscles from those of the static hip stabilizers. The muscle state without load represents the collective contributions from soft tissues that were not removed during specimen preparation, including the capsuloligamentous complex, femoral head and labrum suction seal, and ligamentum teres. These tissues resisted internal rotation and permitted external rotation with increasing hip flexion from 0° to 90° (Figures 2 and 3). They also displayed a linear resistance pattern to distractive forces that provided most resistance toward 0° and 90° of hip flexion (Figure 4). These findings are comparable with those of a cadaveric study by van Arkel et al,[24] who found that the capsular ligaments provided minimal resistance to rotation in midflexion and neutral abduction/adduction, but limited rotation by decreasing slack towards the extremes of flexion and extension. The same authors also found in a separate study that the capsular ligaments contribute significantly more rotational restraint through hip range of motion compared with the labrum and ligamentum teres.[23]

Limitations

Numerous limitations should be considered when interpreting this study. First, the cadaveric hip model was simplified to bony anatomy, capsuloligamentous structures, femoral head and labrum suction seal, and the GMin and GMax distal insertions and therefore did not comprehensively analyze all structures that contribute to dynamic hip stability in vivo. Second, since the static stabilizers of the hip were not removed to maintain the femoral head center, they inevitably confounded the individual and collective contributions of the GMin and GMed. Third, the force and direction of pull of the GMin and GMed were estimations based on anatomic approximations and previous studies to ease reproducibility of the model. Fourth, pelvic positioning was standardized and did not accurately account for variations such as pelvic tilt in the general population that can affect hip biomechanics. Fifth, variations in bony anatomy such as dysplasia, abnormal femoral and acetabular version, and pincer and cam FAI lesions of the hip joint that could influence stability of the hip joint were not quantified. Sixth, this study tested the contributions of the abductors in neutral stance from 0° to 90° of hip flexion, but did not obtain data regarding hip stability with respect to abduction or adduction. Seventh, with biomechanical testing using forces up to 390 N, it could not be confirmed that muscle fascicles of the GMin and GMed did not tear at the microscopic level and thereby affect the load transfer and accuracy of measurements. Similarly, testing order was not randomized but rather performed sequentially, which could theoretically affect subsequent measurements if tissues tear or stretch. However, this study did not involve extensive cyclic loading. Eighth, since fresh-frozen specimens were used for this study the true mechanical properties of the GMin and GMed as well as other stabilizers of the hip may have been altered compared with nonfrozen tissues. Ninth, the sexes of the specimens were not balanced (7 male and 3 female), so the findings can be confounded by distinct pelvic anatomical differences between sexes. Finally, the measurements recorded in this study were static and do not accurately represent the normal hip function and physiology in dynamic living human beings.

CONCLUSION

We present the findings from a biomechanical cadaveric model of the hip focusing on the GMin and GMed. We found that both the GMin and GMed stabilized the hip against internal and external rotation torques and femoral distraction forces to an extent based on the degree of hip flexion. These findings have clinical implications for therapies that emphasize hip abductor strengthening to address pathologies related to hip instability. Moreover, this biomechanical cadaveric model can be easily reproduced and used to investigate other dynamic biomechanical relationships of the hip abductor complex and associated pathologies.

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