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Hip kinematics during single leg tasks in people with and without hip-related groin pain and the association among kinematics, hip muscle strength and bony morphology

Marcie Harris-Hayes, PT, DPT, MSCI[1,4], **Travis J. Hillen, MD**[2], **Paul K. Commean, BEE**[3], **Michael D. Harris, PhD**[1,4,5], **Michael J. Mueller, PT, PhD, FAPTA**[1,2], **John C. Clohisy, MD**[4], **Gretchen B. Salsich, PT, PhD**[6]

[1]Program in Physical Therapy, Washington University School of Medicine, St. Louis, MO, United States

[2]Department of Radiology, Washington University School of Medicine, St. Louis, MO, United States

[3]Electronic Radiology Lab in Mallinckrodt Institute of Radiology, Washington University School of Medicine, St Louis, MO, United States

[4]Department of Orthopaedic Surgery, Washington University School of Medicine, St Louis, MO, United States

[5]Department of Mechanical Engineering and Materials Science, Washington University, St. Louis, MO, United States

[6]Program in Physical Therapy, Saint Louis University, 3437 Caroline St., St. Louis, MO. 63104, United States.

Abstract

OBJECTIVE: To compare 3D hip kinematics during single leg squat (SLsquat) and step down, between patients with hip-related groin pain (HRGP) and asymptomatic participants. To assess relationships among hip kinematics, muscle strength and bony morphology.

DESIGN: Controlled laboratory cross-sectional study.

METHODS: 40 patients with HRGP and 40 matched, asymptomatic participants, 18–40 years. Hand-held dynamometry was used to assess hip abductor and external rotator strength. An 8-camera motion analysis system was used to quantify 3D kinematics during SLSquat and step down. MRI was used to quantify bony morphology. Independent t-tests and Mann-Whitney U tests

Correspondence: Marcie Harris-Hayes, DPT, MSCI, Program in Physical Therapy and Department of Orthopaedic Surgery, Washington University School of Medicine, 4444 Forest Park, Campus Box 8502, St. Louis, MO, 63108, United States, Phone: (314)-286-1435, Fax: (314)-286-1410, harrisma@wustl.edu.

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Statement of Institutional Review Board Approval
The study was approved by the Human Research Protection Office at Washington University School of Medicine and all participants signed an informed consent statement prior to participation in the study.

were used to assess between-group differences. Pearson coefficient correlations were used to assess relationships.

RESULTS: Patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles and lesser squat depth compared to asymptomatic participants during SLSquat. Among patients with HRGP, smaller hip flexion angles during SLSquat were associated with hip abductor weakness (r=.47, P = <.01). Among asymptomatic participants, smaller peak hip flexion angles during SLSquat were associated with less acetabular coverage (r=.33, P =.04) and shallow squat depth (r = .48, P = <.01); smaller hip internal rotation angle during step down was associated with larger femoral neck shaft angle (r=−.43, P = <.01).

CONCLUSION: Compared to asymptomatic participants, patients with HRGP had smaller hip and knee flexion angles and shallower squat depth during single leg squat. Smaller hip flexion angles were associated with hip abductor weakness among those with HRGP.

Keywords

femoroacetabular impingement; dysplasia; movement

INTRODUCTION

Hip-related groin pain (HRGP)[30] in young to middle aged adults, due to conditions such as femoroacetabular impingement syndrome (FAIS), acetabular dysplasia and labral tears, contribute to substantial pain and activity limitations. The multifactorial nature of these conditions is unclear. Understanding the role hip kinematics may play in HRGP in context with muscle strength and bony morphology, will improve clinicians' ability to tailor appropriate treatment. In particular, high demand, single leg tasks may provide an opportunity to detect impaired kinematics that may not occur during gait or bilateral squat. Single leg tasks, such as a single leg squat (SLSquat) and step down, require sufficient neuromuscular performance to maintain balance and quality of limb movement through a large and challenging range of motion.[5, 13] To better understand the relationships among kinematics, bony morphology, muscle strength and HRGP, investigations are needed to assess the performance of movement tasks of varying difficulty.

Relationships among hip kinematics, hip muscle strength and bony morphology have not been established. Hip abductor and external rotator (ER) strength play an important role during daily tasks such as maintaining pelvic position during stance and providing stability to the hip.[18, 29] Patients with HRGP have hip muscle weakness.[4, 5, 8] Muscle weakness may contribute to abnormal hip kinematics, however the evidence reporting this relationship is limited. Previous studies assessing bony morphology and hip kinematics among patients with HRGP have focused primarily on cam and pincer morphology associated with FAIS,[5, 13, 17] and few have directly assessed the relationship between bony morphology and hip kinematics.[6, 19] The relationship between hip kinematics and femoral version -- the relative rotation between the femoral neck and femoral shaft (FemVer) -- and the femoral neck-shaft angle (FNSA) is unclear.

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Our primary goal was to compare 3D hip kinematics during SLSquat and step down, between patients with HRGP and asymptomatic participants. We expected patients with HRGP would have increased hip adduction and internal rotation (IR) motion during both tasks compared to asymptomatic participants. A secondary purpose was to assess the relationships among hip kinematics, hip muscle strength and bony morphology among those with HRGP and asymptomatic participants. Regardless of participant group, we hypothesized that larger hip adduction angles would be associated with hip abductor weakness, larger FNSA and smaller lateral center edge angles (LCEA, indicating acetabular dysplasia); smaller peak hip flexion angles would be associated with a larger alpha angle (MaxAlpha, indicating cam morphology); and larger hip IR angles would be associated with ER weakness and larger FemVer angles.

METHODS

The study was approved by the Human Research Protection Office at Washington University and all participants signed an informed consent statement prior to participation.

Study Design and Participants

This was a cross-sectional cohort study to investigate mechanical factors associated with HRGP. People with and without HRGP, aged 18 to 40 years, in the St. Louis, MO region were recruited from the community, healthcare clinics and the Washington University research registry. Participants with HRGP had to report groin or deep hip joint pain that had been present greater than three months and rated, on average, greater than 3/10 (10 = worst imaginable) on a numeric pain scale. Pain had to be reproduced with the flexion, adduction and IR test (FADIR). Asymptomatic participants reported no history of hip or current lower extremity pain and were matched to those with HRGP 1:1 by sex, age (5 years), BMI (5 kg/m^2) and limb side. Exclusion criteria for both groups were (1) history of hip surgery or fracture, (2) BMI greater than 30 kg/m^2, (3) contraindication to MRI, (4) neuromuscular deficits that affected coordination or balance, (4) pregnancy or (5) screening exam indicated possible lumbar spine radiculopathy.

Testing Procedures

Prior to testing, participants completed self-report questionnaires including (1) demographics and medical history, (2) University of California Los Angeles activity score (UCLA)[1, 31] (3) Hip Osteoarthritis and disability Outcome Score (HOOS)[15] and (4) Modified Harris Hip Score (MHHS).[3, 22]

Hip Muscle Strength—Prior to strength assessment, participants completed a five-minute warm-up using stationary bike or treadmill. A microFET3 (Hoggan Health Industries, Salt Lake City, UT) handheld dynamometer was used to assess hip muscle strength.[8] Break tests[10, 16] were performed to determine maximum force in Newtons. After familiarization, three trials using maximal effort were collected.

Hip ER strength was assessed in sitting with test hip in 90° flexion, 0° abduction and end-range IR. Hip abductor strength was assessed in sidelying with test hip in 15° abduction, 0°

flexion and 0° rotation. For each strength variable, we averaged three maximal trials and multiplied the value by the associated moment arm to calculate torque. Because our study included men and women, we normalized torque by weight and height.[2] Test-retest reliability of our methods is good: abductors ($ICC_{3,3}$ = 0.94, standard errors of measurement [SEMs] = .47Nm/Nm), ERs ($ICC_{3,3}$ = 0.89, SEM = .39Nm/Nm).[8]

Hip Joint Kinematics—The primary kinematic variables were hip joint angles captured at peak hip flexion for each task.[28] Three-dimensional kinematic data were collected using an 8-camera motion capture system (Vicon Nexus, Los Angeles, LA) sampling at 120Hz. Retro-reflective markers were placed on anatomical landmarks representing the pelvis, thigh and lower leg.[28] Rigid four-marker clusters for tracking were placed at the thigh and lower leg. Participants performed SLSquat, followed by step down. For each task, the participant practiced 2–3 times, then three trials were collected. Participants rated pain experienced during each trial (0 = no pain, 10 = worst imaginable).

Single leg squat: Participants were instructed to place their arms across their chest, flex the opposite knee to position their foot behind their body, then squat as low as possible.[11, 28] For a trial to be valid, the participant had to squat and return to standing without losing balance and while keeping their weight bearing foot flat on the floor. No specific cues for trunk position were provided.

Step down: Step height was selected according to participant height; 15.2 cm for height <163 cm, 20.3 cm for height 163 – 180 cm and 25.4 cm for height >180 cm. Participants were instructed to place their arms across chest and step forward off the step with their opposite limb, "tap" the floor with their heel, then return. For a trial to be valid, the participant had to lightly tap the floor, visually assessed by the examiner, and return without losing balance.

Kinematic data were processed by a blinded research assistant, using Visual 3D software (C-Motion Inc, Germantown, MD).[28] Marker trajectories were low-pass filtered using a fourth-order Butterworth filter with a 6-Hz cutoff frequency. We used a 6-degrees-of-freedom model using the Codamotion model (Charnwood Dynamics Ltd, Leicestershire, UK) to define the pelvis, and a functional hip joint center[25] and femoral epicondyle markers to define the thigh. To assess squat depth, excursion of a virtual marker, midpoint between the posterior superior iliac spine markers, was obtained and divided by participant height. We averaged the 3D joint angles, assessed at peak hip flexion, for each participant. *A priori*, we chose to analyze motion at peak hip flexion because positions of hip flexion, combined with hip adduction and IR may contribute to HRGP. We established our test-retest reliability by performing two assessments of SLSquat, a minimum two weeks apart, with ten asymptomatic participants. Reliability was excellent for hip flexion ($ICC_{3,3}$ = .90, SEM = 4.1°) and moderate for hip adduction and IR ($ICC_{3,3}$ = .88, SEM = 1.4° and $ICC_{3,3}$ = .86, SEM = 1.4°).

Bony Morphology—We have previously published our methods using MRI to determine measures of bony morphology.[7] Briefly, a 1.5-Tesla magnetic resonance system (MAGNETOM Avanto; Siemens, AG, Munich, Germany) was used to acquire 3D fat-

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suppressed gradient-echo sequences centered at the pelvis and distal femora, both acquired in the coronal plane. Standardized procedures were used to optimize participant positioning.[7] The following parameters were used: slice thickness 0.82mm, Repetition time (TR) 15.96ms, Echo time (TE) 6.2ms, Field of view (FOV) 400mm at the pelvis and distal femora, 512×512 matrix.

An independent workstation (LEONARDO; Siemens) was used for post-processing to create 2D pelvic images for FemVer angle, FNSA, alpha angles and LCEA. To obtain images for alpha angles at the 12, 1, 2 and 3 o'clock location on the femoral head-neck junction, a radial reformat was performed along the femoral neck axis at 30° intervals. For each participant, we used the maximum alpha angle (MaxAlpha) value among the four clock-face locations in the analysis. A blinded research assistant completed measurements using ANALYZE 11.0 software (Biomedical Imaging Resource, Mayo Foundation, Rochester, MN). Inter-rater reliability of our methods has been reported previously[7] and are excellent for FNSA ($ICC_{2,1}$ = 0.96, SEM = 1.1°) and FemVer angle ($ICC_{2,1}$ = 0.97, SEM = 1.1°) and good for LCEA ($ICC_{2,1}$ = 0.86, SEM = 2.0°) and MaxAlpha ($ICC_{2,1}$ = 0.78, SEM = 2.6°).

Statistical Analysis

The study was designed with a target enrollment of 80 participants. Using preliminary data collected in our lab, an *a priori* power calculation indicated a sample size of 40 per group would provide statistical power of at least 0.80 to detect differences in our primary variables, including hip adduction and IR angles during SLSquat and hip abductor strength, with effect sizes of at least 0.64 at an alpha of .05 using 2-tailed tests. We used the Kolmogorov-Smirnov test to assess distribution of data and Levene's test to assess equality of variance. Between-group comparisons were performed using independent-samples *t* tests and the Mann-Whitney U tests for continuous and ordinal data, respectively. Pearson coefficient correlations were used to assess the relationships among kinematics, muscle strength and bony morphology. A *P* value less than .05 was considered significant.

RESULTS

Between-Group Comparisons

Eighty participants were enrolled. There were no group differences in demographic data (Table 1). Patients with HRGP demonstrated smaller peak hip flexion angles (68.8°±14.6° vs. 76.4° ±16.8°, *P* = .03), smaller knee flexion angles assessed at peak hip flexion (66.9° ±8.5° vs. 71.2° ±9.6, *P* = .04) and shallower squat depth (9.8% ± 2.2% vs. 10.9% ± 2.7%, *P* = .04), compared to asymptomatic participants during SLSquat. There were no differences in hip adduction or IR angles during SLSquat and no differences in kinematics during step down (Table 2). Patients with HRGP were weaker compared to asymptomatic participants (Table 2). There were no differences in measures of bony morphology (Table 2).

Correlations

Among patients with HRGP (Table 3), weaker hip abductor strength was associated with smaller hip flexion angles during SLSquat (r = .47, *P* = <.01). There were no associations between hip kinematics and muscle strength during the step down task. Bony morphology was not associated with hip kinematics during either task.

Among asymptomatic participants (Table 4), there were no associations between hip muscle strength and hip kinematics during SLSquat or step down. Smaller peak hip flexion angles during the SLSquat were associated with smaller LCEAs (r = .33, $P = .04$). Larger FNSAs, were associated with smaller hip IR angles during the step down (r = −.43, $P = 01$).

A Posteriori Assessment

Peak hip flexion angles were similar between those with HRGP who reported pain during SLSquat (n=20) and those who did not (69.7° ± 14.3° vs. 68.8° ± 14.5° respectively, $P = .85$).

DISCUSSION

Patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles and shallower squat depth during SLSquat compared to asymptomatic participants. We found no differences in step down kinematics. Despite weakness in hip abductors and ERs, and reporting long pain duration, patients with HRGP had similar hip adduction and rotation angles during both tasks compared to asymptomatic participants. Among those with HRGP, smaller peak hip flexion angles during SLSquat were associated with hip abductor weakness.

We are unsure why patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles and lesser squat depth compared to asymptomatic participants. Pain during testing did not appear to influence hip flexion angles during SLSquat. Hip flexion angles were similar between those with HRGP who reported pain and those who did not. The differences may be associated with other factors such as hip muscle weakness, adjacent joint kinematics or other unmeasured variables.

Among patients with HRGP, smaller hip flexion angles were associated with reduced hip abductor strength (Table 3). Due to the cross-sectional nature of our study, we cannot establish the temporal relationship between hip abductor strength and hip flexion angles. We did not collect muscle activation or kinetic data. Therefore we cannot draw conclusions regarding muscle activity or joint loading patterns. Hip muscle weakness has been noted among patients with HRGP,[4, 5, 8] and represents a modifiable target for rehabilitation. We did not assess ankle or trunk kinematics, which may influence hip kinematics. Given the modest relationships noted, other factors such as fear, anticipation of pain provocation[27] or poor neuromuscular control, may explain the differences.

Unlike SLSquat, peak hip flexion angles during step down were similar between groups. The step down requires smaller hip flexion angles than SLSquat (Table 2). Group differences in peak hip flexion angles may have been observed, if participants were required to go through greater range of motion. Our findings are in contrast to previous work,[17] however methodological differences between our study and previous research might explain the conflicting results. We matched patients with HRGP and asymptomatic participants, thus 40

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in each group. The previous study compared 20 patients with FAIS to 40 asymptomatic participants. Hip flexion values in patients with FAIS in the previous study, may have approached those of asymptomatic participants if more patients had been enrolled. Patients with HRGP in our study had varied bony morphology, however exploration of a subset comparing patients with FAIS to participants without impingement morphology (n = 8 pairs) showed a similar trend to our reported findings for hip flexion. Our testing methods likely resulted in a more challenging task by using a higher step height, analyzing kinematics at larger hip and knee flexion angles and potentially shifting the participant's center of mass superoanteriorly by placing the arms across the chest instead of at the side. Each of these methodological differences could influence hip kinematics.

There were no group differences in hip kinematics in hip adduction or rotation angles during either task. Previous work also found no differences in hip adduction between asymptomatic participants and those with FAIS.[17] There were large standard deviations relative to group means, suggesting that people in both groups had a wide range of movement patterns. It is possible that abnormal kinematics, such as excessive hip adduction exists in a subgroup of people,[24, 28] despite presence or absence of pain, and may precede injury. However, to our knowledge, the relationship of hip kinematics and pain onset has not been studied prospectively.

Among asymptomatic participants, hip kinematics were associated with bony morphology, but not hip muscle strength (Table 4). Less acetabular coverage was associated with smaller peak hip flexion angles during SLSquat, and larger FNSAs were associated with smaller hip IR angles at peak hip flexion during step down. In contrast, Souza et al[26] reported no association between FNSA and hip IR angles during running among asymptomatic women. Differences may be due to the tasks assessed. We did not find a correlation between hip kinematics and cam morphology or FemVer during either task. We were surprised to observe relationships between bony morphology and kinematics among asymptomatic participants but not among patients with HRGP. Our sample was relatively small and bony morphology values may not represent the variability of a larger population. In future, larger studies may provide insight to the relationship between bony morphology and hip kinematics.

Limitations

Our patient sample represents a heterogeneous population. While all patients reported long duration of deep hip joint and/or anterior groin pain, the source of their symptoms may vary. To be enrolled, the patient's history had to be consistent with HRGP and their groin pain had to be reproduced with the FADIR test. Given the FADIR test is sensitive, but not specific,[23] we collected history information and performed screening tests to rule out pain referred from other sources. It is possible that pain may be due to other groin pain entities such as iliopsoas-related groin pain.[30] Fourteen participants (10 HRGP; 4 asymptomatic) had cam morphology (MaxAlpha 60°) or pincer morphology, (LCEA 40˚), and 3 (1 HRGP; 2 asymptomatic) had acetabular dysplasia (LCEA 20°). We did not perform additional diagnostic imaging to determine if a labral tear or chondral lesion was present. Our ultimate goal, to be pursued in a larger, prospective study is to better understand the interaction of the

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multiple factors associated with HRGP, we therefore designed our study to be inclusive of hip joint conditions.

Our small sample of 40 patients with HRGP limits our ability to adequately assess multifactorial relationships among patient characteristics (sex, BMI, age, etc.), hip kinematics, muscle strength, bony morphology and patient-reported activity limitations (HOOS, MHHS). Our study provides preliminary data to assist in designing a larger study to better assess these relationships. Strength assessment was limited to hip abductors and ERs. Other lower extremity muscles may play a role in hip kinematics.[12, 14, 21] We do not know if our kinematic reliability measures are generalizable to the symptomatic group, because we completed reliability testing among asymptomatic participants only. Research investigating movement variability across a number of trials for specific tasks instead of averaging all trials, may provide further insight to group differences in movement.

CONCLUSIONS

Compared to asymptomatic participants, patients with HRGP had smaller peak hip flexion angles, smaller knee flexion angles and shallower squat depth during SLSquat. Smaller hip flexion angles during SLSquat were associated with hip abductor weakness among those with HRGP.

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KEY POINTS

Findings:

Patients with hip-related groin pain (HRGP) had smaller peak hip flexion angles, smaller knee flexion angles and shallower squat depth during a single leg squat compared to those without symptoms. Smaller hip flexion angles were associated with hip abductor weakness among those with HRGP.

Implications:

Abnormal lower extremity movement patterns and muscle weakness may be appropriate targets for rehabilitation among patients with HRGP.

Caution:

The patients with HRGP who were included in this study represent a heterogeneous sample including different hip pain conditions such as femoroacetabular impingement syndrome and acetabular dysplasia.

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Table 1.

Demographic characteristics for both groups and descriptive data reporting pain and patient-reported outcome measures in participants with hip-related groin pain.

Demographics	HRGP n=40	Control n=40	P
Sex	33F:7M	33F:7M	
Age, years[*]	28.2 ± 4.9	27.6 ± 5.5	0.62[†]
BMI, kg/m^2[*]	24.1 ± 3.0	24.0 ± 2.5	0.88[†]
UCLA[‡][//]	9 (3–10)	10 (4–10)	0.15[§]
Pain duration, years[//]	2 (0.4–13)	-	-
HOOSPain[‡]	75.4 ± 14.7	-	-
HOOSSymptoms[‡]	71.9 ± 17.1	-	-
HOOSADL[‡]	89.9 ± 11.2	-	-
HOOSSport[‡]	72.5 ± 21.4	-	-
HOOSQOL[‡]	58.7 ± 21.7	-	-

Abbreviations: HRGP, hip-related groin pain; BMI, body mass index; UCLA, University of California Los Angeles Activity Score; HOOS, Hip Disability and Osteoarthritis Outcome Score; ADL, function in activities of daily living; Sport, function in sports and recreation; QOL, quality of life

[*] Value is mean ± standard deviation.

[†] Independent sample t-tests were used.

[‡] UCLA: participants are asked to rate their activity level over the previous 6 months. 1=wholly inactive, dependent on others; 10= regularly participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking.

[//] Values are median (range)

[§] Mann-Whitney U Test was performed. One control participant did not complete UCLA.

[‡] Patient-reported outcome measures with 100=no disability. Values are means ± standard deviation.

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Table 2.

Between-group differences in hip kinematics, muscle strength and bony morphology.

	HRGP Mean ± SD	Control Mean ± SD	P*
Kinematics single leg squat†	N=40	N=40	
Hip flex angle (°)	68.8 ± 14.6	76.4 ± 16.8	.03
Hip add angle (°)	18.6 ± 6.7	18.6 ± 6.9	.98
Hip IR angle (°)	3.8 ± 7.5	1.7 ± 8.6	.25
Knee flex angle (°)	66.9 ± 8.5	71.2 ± 9.6	.04
Knee add angle (°)	3.3 ± 4.8	1.9 ± 6.9	.28
Knee IR angle (°)	2.4 ± 6.8	1.5 ± 7.4	.60
Squat depth (% height)	9.8 ± 2.2	10.9 ± 2.7	.04
Time to complete motion (seconds)	3.1 ± 1.0	2.9 ± 0.9	.42
Kinematics step down†			
Hip flex angle (°)	57.1 ± 12.5	59.7 ± 9.8	.30
Hip add angle (°)	23.4 ± 5.9	23.3 ± 6.2	.94
Hip IR angle (°)	6.5 ± 6.7	5.4 ± 8.1	.52
Knee flex angle (°)	69.7 ± 8.1	73.0 ± 6.4	.05
Knee add angle (°)	5.0 ± 5.0	4.0 ± 6.6	.44
Knee IR angle (°)	2.9 ± 6.6	2.3 ± 7.7	.72
Time to complete motion (seconds)	4.0 ± 1.0	3.8 ± 1.1	.29
Muscle Strength†	N=40	N=40	
Hip ER	3.5 ± 0.8	4.2 ± 1.1	<.01
Hip Abd	6.9 ± 2.0	8.9 ± 1.7	<.01
Bony morphology	N=38//	N=38//	
FNSA (°)	135.4 ± 4.5	133.7 ± 4.7	.13
FemVer (°)	9.1 ± 9.3	10.5 ± 7.5	.45
MaxAlpha (°)	53.7 ± 7.7	51.7 ± 8.6	.32
LCEA (°)	30.3 ± 6.4	30.8 ± 6.0	.76

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Abbreviations: HRGP, hip-related groin pain; SD, standard deviation; flex, flexion; add, adduction; IR, internal rotation; ER, external rotators; Abd, abductors; FNSA, femoral neck-shaft angle; FemVer, femoral version (larger values indicate femoral anteversion);MaxAlpha, maximum alpha angle; LCEA, lateral center edge angle

[*] Independent sample t-tests were used.

[†] Hip and knee kinematic variables were extracted at peak hip flexion angle.

[‡] Muscle torque is normalized by body weight X height X 100.

[//] Due to technical issues, MRI data was not available for three participants, therefore we included only those pairs in which we had imaging data for both participants among the matched pairs.

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Table 3.

Associations among hip kinematics, hip muscle strength and bony morphology variables among patients with hip-related groin pain.

	Hip flex angle (°)*	Hip add angle (°)*	Hip IR angle (°)*	Knee flex angle (°)*	Knee add angle (°)*	Knee IR angle (°)*	Hip ER str†	Hip abd str†	FNSA (°)	FemVer (°)	MaxAlpha (°)	LCEA (°)	Squat depth (% height)
Single Leg Squat Task													
Hip flex angle (°)*		.05	−.24	.28	.13	.14	.23	**.47**	−.14	.02	.07	−.20	.30
***P* value**		.76	.13	.08	.42	.39	.16	**<.01**	.41	.91	.69	.24	.07
Hip add angle (°)*			.21	−.13	−.12	**.36**	−.07	−.10	.01	−.07	−.17	.08	.03
***P* value**			.20	.42	.45	**.02**	.68	.54	.95	.66	.30	.62	.88
Hip IR angle (°)*				−.14	**.41**	−.11	−.11	−.23	.04	.17	−.06	.11	−.07
***P* value**				.41	**<.01**	.49	.51	.16	.81	.32	.72	.51	.67
Knee flex angle (°)*					.21	**.36**	.21	.12	−.13	.28	.07	**−.46**	**.89**
***P* value**					.20	**.02**	.20	.47	.45	.08	.66	**<.01**	**<.01**
Knee add angle (°)*						**.43**	.28	.26	−.09	−.09	**.34**	−.10	**.39**
***P* value**						**<.01**	.05	.10	.58	.59	**.04**	.54	**.01**
Knee IR angle (°)*							.02	.14	−.13	−.12	.29	−.07	**.44**
***P* value**							.93	.39	.43	.48	.08	.67	**<.01**
Hip ER strength†								**.50**	.10	.07	.09	−.29	.29
***P* value**								**<.01**	.56	.69	.59	.08	.06
Hip abd strength†									.13	−.20	.10	−.09	.14
***P* value**									.42	.23	.54	.61.	.38
FNSA (°)										−.13	−.07	−.32	−.16
***P* value**										.43	.67	.05	.35
FemVer (°)											−.26	−.01	.12
***P* value**											.12	.94	.47
MaxAlpha (°)												−.21	.04
***P* value**												.21	.82

	Hip flex angle (°)*	Hip add angle (°)*	Hip IR angle (°)*	Knee flex angle (°)*	Knee add angle (°)*	Knee IR angle (°)*	Hip ER str†	Hip abd str†	FNSA (°)	FemVer (°)	MaxAlpha (°)	LCEA (°)	Squat depth (% height)
LCEA (°)													−.52
***P* value**													**<.01**
Squat depth (% height)													
P value													
Step Down Task													
Hip flex angle (°)*		.24	−.17	**.47**	−.13	.02	−.10	.21	.14	.06	−.00	−.03	
***P* value**		.13	.31	**<.01**	.45	.89	.53	.20	.41	.74	.98	.85	
Hip add angle (°)*			.07	.06	−.14	−.23	.00	.14	.22	.12	−.29	−.12	
***P* value**			.68	.71	.40	.17	.98	.40	.19	.47	.08	.48	
Hip IR angle (°)*				−.22	**.73**	.03	.41	−.01	−.24	.24	−.11	.14	
***P* value**				.19	**<.01**	.85	.39	.97	.15	.16	.95	.40	
Knee flex angle (°)*					.07	.32	.31	**.36**	.20	.15	.19	**−.50**	
***P* value**					.67	.05	.05	**.02**	.23	.38	.27	**<.01**	
Knee add angle (°)*						**.37**	.30	.19	−.09	.12	.19	.03	
***P* value**						**.02**	.06	.24	.61	.47	.26	.85	
Knee IR angle (°)*							.08	.31	−.03	−.21	**.40**	−.09	
***P* value**							.63	.05	.86	.21	**.01**	.58	

Abbreviations: flex, flexion; add, adduction; IR, internal rotation; ER, external rotators; Abd, abductors; FNSA, femoral neck-shaft angle; FemVer, femoral version (larger values indicate femoral anteversion);MaxAlpha, maximum alpha angle; LCEA, lateral center edge angle

Bold indicates p<.05

*Hip and knee kinematic variables were extracted at peak hip flexion angle.

†Muscle torque is normalized by body weight X height X 100.

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Table 4.

Associations among hip kinematics, hip muscle strength and bony morphology variables among asymptomatic participants.

	Hip flex angle (°)*	Hip add angle (°)*	Hip IR angle (°)*	Knee flex angle (°)*	Knee add angle (°)*	Knee IR angle (°)*	Hip ER str†	Hip abd str†	FNSA (°)	FemVer (°)	MaxAlpha (°)	LCEA (°)	Squat depth (% height)
Single Leg Squat Task													
Hip flex angle (°)*		.25	**−.39**	**.41**	.21	.04	−.04	.03	−.03	−.03	−.07	**.33**	**.48**
***P* value**		.13	**.01**	**.01**	.19	.82	.80	.84	.85	.87	.65	**.04**	**<.01**
Hip add angle (°)*			−.25	−.10	−.05	**−.37**	−.02	.09	.20	.09	.15	.05	.05
***P* value**			.12	.54	.74	**.02**	.91	.57	.22	.61	.35	.75	.75
Hip IR angle (°)*				.07	**.58**	.19	.20	−.11	−.31	.15	.15	−.05	.04
***P* value**				.65	**<.01**	.25	.21	.52	.06	.36	.35	.78	.81
Knee flex angle (°)*					**.39**	.17	**.35**	.05	−.15	.17	.07	−.11	**.91**
***P* value**					**.01**	.29	**.03**	.75	.36	.31	.69	.51	**<.01**
Knee add angle (°)*						.25	.21	.05	**−.52**	−.01	−.01	.18	**.44**
***P* value**						.12	.19	.76	**01**	.97	.96	.28	**<.01**
Knee IR angle (°)*							.04	.04	−.15	−.02	−.24	−.20	.09
***P* value**							.82	.81	.37	.89	.14	.21	.60
Hip ER strength†								**.53**	−.01	−.04	**.35**	**−.39**	.31
***P* value**								**<.01**	.94	.82	**.03**	**.01**	.05
Hip abd strength†									.01	.04	.29	−.29	.05
***P* value**									.95	.81	.07	.07	.76
FNSA (°)										−.02	−.14	−.11	−.16
***P* value**										.91	.40	.51	.33
FemVer (°)											.20	−.04	.13
***P* value**											.22	.79	.44
MaxAlpha (°)												−.19	.11
***P* value**												.24	.53

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	Hip flex angle (°)*	Hip add angle (°)*	Hip IR angle (°)*	Knee flex angle (°)*	Knee add angle (°)*	Knee IR angle (°)*	Hip ER str†	Hip abd str†	FNSA (°)	FemVer (°)	MaxAlpha (°)	LCEA (°)	Squat depth (% height)
LCEA (°)													−.01
***P* value**													.93
Squat depth (% height)													
***P* value**													
Step Down Task													
Hip flex angle (°)*		**.54**	**−.56**	.09	−.30	−.06	−.23	.05	.23	−.03	−.10	.21	
***P* value**		**<.01**	**<.01**	.58	.06	.73	.15	.76	.15	.85	.55	.19	
Hip add angle (°)*			**−.45**	−.22	**−.49**	−.32	−.21	−.04	.23	.12	.00	−.04	
***P* value**			**<.01**	.17	**<.01**	.05	.19	.81	.16	.48	.99	.82	
Hip IR angle (°)*				−.08	**.74**	.14	.18	−.17	**−.43**	.08	−.06	.08	
***P* value**				.61	**<.01**	.39	.26	.30	**<.01**	.63	.70	.61	
Knee flex angle (°)*					.15	.17	.19	−.01	−.02	.18	−.05	−.10	
***P* value**					.35	.29	.24	.94	.91	.27	.79	.54	
Knee add angle (°)*						.22	.30	.06	**−.54**	−.12	−.04	.21	
***P* value**						.18	.06	.70	**<.01**	.48	.79	.19	
Knee IR angle (°)*							−.02	.02	−.26	−.07	−.07	−.12	
***P* value**							.90	.92	.12	.68	.66	.48	

Abbreviations: flex, flexion; add, adduction; IR, internal rotation; ER, external rotators; Abd, abductors; FNSA, femoral neck-shaft angle; FemVer, femoral version (larger values indicate femoral anteversion);MaxAlpha, maximum alpha angle; LCEA, lateral center edge angle

Bold indicates p<.05

* Hip and knee kinematic variables were extracted at peak hip flexion angle.

† Muscle torque is normalized by body weight X height X 100.