The Influence of Lateral and Posterior Total Hip Arthroplasty Approaches on Muscle Activation and Joint Mechanics during Gait

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Abstract

Background: Lateral and posterior total hip arthroplasty (THA) approaches disrupt muscle function, which could impact gait. The objectives of this study were to compare muscle activation and joint mechanics during gait, and isometric strength between participants after lateral and posterior THA approaches and healthy adults.

Methods: Participants 1 year post-THA from either lateral (n=21) or posterior (n=21) approaches, and healthy adults (n=21) ambulated at self-selected speeds. Surface electromyography, optical motion capture, and force plates measured muscle activation and joint mechanics during gait. A dynamometer measured isometric torque. Gait characteristics and isometric torque were compared using analysis of variance and effect sizes (d).

Results: Lateral THA group had higher gluteus medius amplitudes during gait compared to the healthy group ($p<0.01$, $d=-0.97$). Posterior THA group had higher gluteus maximus amplitudes during loading response ($p=0.02$, $d=-0.94$) and higher hamstring amplitudes during midstance ($p=0.02$, $d=0.45$ to 1.31) than the healthy group. Both THA groups had decreased hip flexion and adduction angle excursions during gait ($d=0.89$ to 1.14), but increased medial rotation angle excursions ($d=-1.06$ to -0.91), compared to the healthy group. Lateral THA group had lower isometric hip abduction torque than the healthy group ($p=0.03$, $d=0.74$). There was no pelvic drop in the THA groups.

Conclusion: There were few differences in gait and isometric torque between lateral and posterior THA groups. The elevated muscle activation amplitudes in the lateral and posterior THA groups compared to healthy adults were likely due to muscle weakness. Despite these findings, there was no evidence of pelvic drop.

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Introduction

Over 90,000 total hip arthroplasties (THA) were performed in the United States in 2016 [1]. The two most common surgical approaches are posterior and direct lateral [2]. Distinct muscles are disrupted with lateral (gluteus medius and minimus) and posterior (gluteus maximus, short lateral rotators, piriformis) approaches potentially leading to different patterns of muscle weakness [3]. For instance, gluteus medius partial denervation and isometric hip abduction weakness were more common after a lateral compared to a posterior THA approach [4,5]. Also, the occurrence of Trendelenburg signs during gait (contralateral pelvic drop indicating gluteus medius weakness) was more common in patients that had a lateral compared to a posterior approach [6]. In contrast, other studies have found no differences in isometric hip abduction between approaches 3 months to 2 years post-THA [7,8]. Inconsistency in findings could be due to differences in testing procedures and time since THA. Regardless, weakness in hip muscles after THA is possible and this could affect functional mobility, such as gait.

The impact of surgical approach on gait has been studied [9]. There were no differences in spatiotemporal parameters, pelvis angles, and hip angles during gait in patients that underwent lateral or posterior THA approaches 6 weeks to 1 year post-surgery [5,10-13]. However, patients that had a posterior THA approach had greater frontal hip moments and power than patients that had a lateral THA approach in the early stages of recovery [9,13]. Additionally, there was increased lateral trunk lean, a compensation for weak hip abductors, in patients that had a lateral compared to a posterior approach 6 weeks post-THA, but not at 12 weeks [12]. Thus, few

[1] PC=principal component; PC-scores= principal component scores; HOOS=Hip Disability and Osteoarthritis Outcome Score; MVIC=maximum voluntary isometric contraction

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differences in gait mechanics exist between THA approaches and differences are likely dependent on recovery time.

Although evidence exists of gluteus medius impairment following lateral approach [5], few studies have examined muscle function during gait. Prolonged and elevated gluteus maximus and medius activation have been demonstrated post-THA compared to healthy adults [14,15]. This could indicate that patients post-THA need to fire more motor units for longer periods of time in order to produce the required muscle force to adequately control the pelvis and femur. However, there is a paucity of research comparing muscle activation during gait between THA approaches. Therefore, the primary objective of this study was to compare muscle activation during gait between participants that had lateral or posterior approaches for THA 1 year post-surgery and healthy adults. It was hypothesized that the lateral approach THA group would have higher gluteus medius activation than the other groups. The secondary objective was to compare joint angles and moments during gait, spatiotemporal gait parameters, isometric strength, and clinical outcomes between these groups. It was hypothesized that there would be no differences in joint angles and moments during gait, spatiotemporal parameters, and clinical outcomes between THA groups. The lateral approach group would have lower isometric hip abduction strength.

Material and Methods

Participants and Design

This cross-sectional study recruited participants that had a THA 1 year previously using convenience sampling from a tertiary hospital (*blinded*) from September 2016 to October 2018. They were included if they had a primary THA for hip osteoarthritis and were between 50 to 80 years of age. Exclusion criteria included revision THA, bilateral THA, severe arthritis in any

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other lower extremity joint, inflammatory arthritis, neurological conditions, or severe cardiovascular conditions. Participants were assigned into either lateral (n=21) or posterior (n=21) THA groups based on the surgical approach they received, which was based on surgeon preference. Additionally, a healthy group (n=21) was recruited from the local community using advertisements. The healthy group had the same exclusion criteria as listed above and additional exclusion criteria for this group included current lower extremity pain, hip osteoarthritis, and previous joint arthroplasty. A flow diagram summarizing the recruitment and exclusion is provided in Figure 1. The study was approved by the local research ethics board, and informed consent was obtained from all participants.

Sample size was based on a previous study that found large effect sizes (d>1.2) for differences in pelvic obliquity angles and hip moments between patients that had posterior or lateral THA approaches [13]. To obtain a large effect (f=0.40) for the planned analysis of variance (ANOVA) comparing the three groups (posterior THA, lateral THA, healthy) with alpha at 0.05 and power of 0.80, the estimated sample size for each group was 21.

Demographic information and surgical information (e.g. surgical data, leg length discrepancy) were collected from self-report or participants' charts. The study leg was the surgical side for the THA groups. The study leg was randomly selected for the healthy group.

THA Surgery

Two surgeons (*blinded*) performed the lateral approach and one surgeon (*blinded*) performed the posterior approach. The surgeons chose the approach based on their training and experience, and they performed their selected surgical approach for all their participants. Posterior approach was performed through a curvilinear incision centered over the greater trochanter posterosuperior aspect. Gluteus maximus was divided. Piriformis and short external

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rotators were removed from their tendinous insertion along with the posterior capsule. The two surgeons performing the lateral approach used the same technique. Lateral approach used a straight incision centered over the greater trochanter extending proximally to the level of the anterior superior iliac spine. Gluteus medius was split such that roughly half of its insertion to the greater tuberosity was preserved. The distal portion was then reflected off the trochanter with a small wafer of bone along with the distal gluteus minimus anterior capsule. Both approaches included repairs that restored the muscle attachments. Participants were prescribed a standard rehabilitation program after surgery during the acute stages of recovery (first week). However, the rehabilitation program afterwards was not standardized as it was tailored to the requirements of each participant.

Clinical Measures

Participants completed the Hip Disability and Osteoarthritis Outcome Score (HOOS), which consists of five subscales with 40 items that measure pain, other symptoms (e.g. stiffness), physical function, sport and recreation, and quality of life [16]. Subscales were transformed to 0-100 scores with higher scores representing better outcomes. Participants also completed three performance measures. The Six-Minute Walk Test required participants to ambulate 6 minutes on a 50 foot (15.24 m) track as fast as possible and the distance covered was measured in meters [17]. The 30-Second Chair Stand Test required participants to complete sit-to-stand repetitions from a standard chair (seat height=46 cm) in 30 seconds as fast as possible without using their arms [18]. The number of complete repetitions was counted. The Stair Climb Test assessed the time in seconds taken to ascend and descend a flight of 11 stairs (stair height=16 cm) as fast as possible [19]. They were permitted to use the railing.

Gait and Torque Data Collection

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Muscle activation was acquired using a wireless surface electromyography (EMG) system sampled at 2000 Hz (Trigno, Delsys Inc.). Electrodes were placed, based on standardized landmarks, over: gluteus medius, gluteus maximus, vastus medialis, vastus lateralis, rectus femoris, medial hamstrings (semitendinosus), lateral hamstrings (biceps femoris), and tensor fascia latae [20,21]. The skin was shaved and thoroughly cleaned with alcohol prior to electrode placement. Muscle palpation and submaximal isometric contractions were performed to validate placement.

Kinematic data were collected using an eight camera, three-dimensional optical motion capture system sampled at 100 Hz (Oqus 3+, Qualisys). Kinetic data were collected using two synchronized force plates, embedded in a walkway, sampled at 2000 Hz (model BP400600-2000, Advanced Mechanical Technology Inc.). Forty reflective markers were placed on participants according to a cluster-based system previously described [22]. Qualisys Track Manager (version 2.8, Qualisys) was used to collect gait data.

Firstly, participants completed a static, standing trial on a force plate to determine joint centers and mass. Next, trials were collected to determine hip joint centers and participants were required to complete hip flexion, extension, abduction and adduction [23]. Participants then performed overground gait trials barefoot at self-selected speeds along an 8 m walkway. They were permitted at least four practice trials. Seven trials were collected, but only five trials were included. Additional trials were collected to account for potential errors. Trials were selected based on the presence of complete marker data and adequate force plate strikes. If all trials were deemed adequate, then the last five trials were selected.

Participants then performed maximum voluntary isometric contraction (MVIC) exercises on an isokinetic dynamometer (Humac Norm, Computer Sports Medicine). Exercises included:

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1) knee extension in sitting with the knee in 45° of flexion; 2) knee flexion in sitting with the knee at 55° of flexion; 3) hip flexion in supine with the hip in 20° of flexion; 4) hip abduction in side-lying with the hip in 0° abduction; and 5) hip extension in prone with the hip in 0° [21,24]. Each exercise included one practice and two collection trials with 30s of rest between trials. MVIC exercises were used to amplitude normalize gait EMG and provide isometric torque measures.

Gait and Torque Data Processing

Data processing was completed using Visual3D (v5, C-motion Inc.). Gait EMG data were band pass filtered (20–500 Hz) using a fourth order recursive Butterworth filter, full wave rectified, and a linear envelope was created by applying a fourth order recursive Butterworth low pass (6 Hz) filter. Similarly, MVIC EMG data were band-pass filtered and full wave rectified. A 100 ms moving-average window identified maximum EMG amplitudes for each muscle during MVIC exercises. Maximum EMG amplitudes were used for gait EMG amplitude normalization.

Marker and force plate data were low pass filtered with a fourth order recursive Butterworth filter with cut off frequencies of 8 and 20 Hz respectively. Hip joint centers were calculated using the functional method [23] and knee joint centers were calculated as the mid-point between medial and lateral epicondyle markers. Hip angles were calculated using an Euler XYZ sequence and positive angles were represented by flexion, adduction, and medial rotation. Pelvis angles were calculated relative to the lab co-ordinate system using Euler ZYX (rotation-obliquity-tilt) sequence [25]. The pelvic obliquity angle in the frontal plane was analyzed as it is controlled by gluteus medius. A positive pelvic obliquity angle indicated a drop on the ipsilateral innominate and elevation on the contralateral innominate. Lateral trunk lean angle was calculated as previously described (positive=ipsilateral trunk lean) [26]. Net external hip moments were

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calculated about the joint coordinate system using inverse dynamics and amplitude normalized to body mass [27]. Gait EMG, angles, and moments were time normalized to 100% of the gait cycle and ensemble averages created from five trials. Spatiotemporal variables were also calculated based on gait events including gait speed, stride length (normalized to height), and stance time (as a percentage of stride).

Torque data from MVIC exercises were filtered using a fourth order recursive Butterworth filter with a 10 Hz cut off frequency. A 500 ms moving-average window identified the maximum torque in each MVIC trial and the highest value from the two trials represented the isometric torque for a MVIC exercise.

Statistical Analysis

Principal component analyses were performed to reduce multidimensionality of gait data and identify important waveform characteristics. Procedures have been described [28,29]. Briefly, separate analyses were created for each muscle group: gluteus medius, gluteus maximus, quadriceps (vastus medialis, vastus lateralis and rectus femoris), hamstrings (medial and lateral hamstrings) and tensor fascia latae. Likewise, separate PCAs were constructed for each joint angle and moment. Eigenvectors, also named principal components (*PCs*), were determined and these represent characteristics of the gait waveforms (e.g. amplitude). Eigenvalues represent the explained variance of *PCs*. Participant ensemble waveforms were scored against *PCs* to produce *PC-scores* and these describe how closely individual waveforms match the *PC*. The principal component analysis was completed using custom written programs in Matlab (2018a, Mathworks).

Descriptive statistics were calculated for study variables. One-way ANOVA, compared groups on demographics, gait *PC-scores*, spatiotemporal gait variables, isometric torque, and

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clinical outcomes. For muscle groups that included more than one muscle (quadriceps, hamstrings), two-way mixed model ANOVAs compared groups and muscles. Bonferroni post hoc tests adjusted for multiple pairwise comparison and mean difference with 95% confidence intervals (CI) were reported. Cohen's d effect sizes for pairwise comparisons were computed and interpreted as small (d=0.20), medium (d=0.50), and large (d=0.80) [30]. Since HOOS subscale scores were not normally distributed, the Kruskal–Wallis H test was used to compare HOOS subscales; following which Man Whitney U tests were used to test for pairwise group differences. Nonparametric effect sizes ($r=Z/\sqrt{N}$) were determined for HOOS and interpreted as small (r=0.10), medium (r=0.30), and large (r=0.50) [31]. SPSS (version 24, IBM) statistical software was used for all statistical analyses.

Results

Demographics are presented in Table 1. The lateral THA group was significantly (p=0.03) older than the posterior THA group. The posterior THA group was significantly ($p<0.05$) taller and heavier than lateral THA and healthy groups, likely because the posterior THA group had a higher proportion of men. The mean time from the TKA procedure to data collection was 13 months for both the lateral (range=11 to 18 months) and posterior (range=11 to 15 months) THA groups. Two participants from the lateral THA group and two participants from the posterior THA group had leg length discrepancies greater than 5 mm according to their medical charts.

Muscle Activation

Mean differences with 95% confidence and effect sizes are presented in Table 2 for muscle activation *PC-scores*. Interpretations of the *PCs* with explained variance (eigenvalues) and ANOVA results are provided in the Supplemental.

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There was a significant difference in gluteus medius *PC1-scores* (p<0.01). The lateral THA group had significantly (p<0.01) higher *PC1-scores*, indicating higher levels of gluteus medius activation throughout gait, than the healthy group (Figure 2). This represented a large effect size (d=-0.97). Additionally, there were significant differences in gluteus medius *PC2-scores* (p=0.01). The lateral THA group had significantly (p=0.01) higher *PC2-scores*, indicating higher gluteus medius activation during mid/terminal stance, than the healthy group (Figure 2). This represented a large effect size (d=-0.95).

There were significant differences in gluteus maximus *PC2-scores* (p=0.02). The posterior THA group had significantly (p=0.02) higher *PC2-scores*, indicating higher gluteus maximus activation during the loading response, than the healthy group (Figure 2). This represented a large effect size (d=-0.94).

There was a significant group effect for hamstring *PC2-scores* (p<0.01), which represented the difference in hamstring activation during midstance compared to terminal swing. The posterior THA group had significantly (p=0.02) lower *PC2-scores*, indicating greater hamstring activation during midstance, than the healthy group (Figure 2). These differences represented moderate to large effect sizes for the medial (d=0.45) and lateral (d=1.31) hamstrings.

There were no other significant group differences for remaining EMG *PC-scores*. Figures for non-significant muscles are provided in the Supplemental.

Joint Angles and Moments

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Mean differences with 95% confidence and effect sizes are presented in Table 3 for angle and moment *PC-scores*. Interpretations of the *PCs* with explained variance (eigenvalues) and ANOVA results are provided in the Supplemental.

For hip flexion angles, there was a significant difference in *PC2-scores* ($p<0.01$). The healthy group had significantly higher *PC2-scores* with large effect sizes, indicating greater flexion angle excursions between terminal swing/loading response and pre/initial swing, than both lateral ($p<0.01$, $d=1.14$) and posterior ($p<0.01$, $d=0.93$) THA groups (Figure 3).

There was a significant difference in hip adduction angle *PC2-scores* ($p=0.01$). The posterior THA group had significantly ($p=0.01$, $d=0.89$) lower *PC2-scores* with a large effect size, indicating less adduction angle excursions between midstance/pre-swing and loading response/swing, compared to the healthy group (Figure 3).

There were significant differences in hip medial rotation *PC2-scores* ($p<0.01$). The heathy group had significantly lower *PC2-scores* with large effect sizes, indicating less medial rotation angle excursions between terminal stance/pre-swing and loading response/terminal swing, compared to lateral ($p=0.01$, $d=-0.91$) and posterior ($p<0.01$, $d=-1.06$) THA groups (Figure 3). Also, there were significant differences in hip medial rotation *PC3-score* ($p<0.01$). The posterior THA group had significantly higher *PC3-scores* with moderate to large effect sizes, indicating greater medial rotation angle excursions between midstance and mid-swing, compared to lateral THA ($p=0.04$, $d=-0.77$) and healthy ($p<0.01$, $d=-1.20$) groups (Figure 3).

There were significant differences in pelvic obliquity angle *PC3-scores* ($p=0.02$). The posterior THA group had significantly ($p=0.02$, $d=0.85$) lower *PC3-scores* with a large effect size compared to the healthy group. This indicated that the posterior THA group had decreased

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excursions from ipsilateral pelvic elevation during mid/terminal stance to ipsilateral pelvic drop during swing (Figure 3).

There were no other significant group differences for the remaining joint angle and all external moment *PC-scores* between groups (Supplemental).

Spatiotemporal Parameters

There were no significant difference in gait speed, stride length, and stance time between the groups (Table 1).

Isometric Torque

From the MVIC exercises, there were only significant differences in isometric hip abduction and knee extension torque (Table 1). The lateral THA group had significantly ($p=0.03$, $d=0.74$) lower isometric hip abduction torque than the healthy group which represented a moderate effect size. The posterior THA group ($p=0.03$, $d=-0.86$) had higher isometric knee extension torque than the healthy group which represented a large effect size.

Clinical Measures

Nonparametric tests revealed significant differences in HOOS subscales (Table 1, Supplemental). Pairwise comparisons revealed the healthy group had higher scores than the lateral THA group on HOOS physical function ($p=0.05$, $r=0.37$) and quality of life ($p<0.01$, $r=0.62$) subscales, which represented moderate to large effects. The healthy group had higher scores than the posterior THA group on HOOS sports ($p=0.03$, $r=0.39$) and quality of life ($p=0.03$, $r=0.40$) subscales, which represented moderate to large effects. There were no significant HOOS differences between posterior and lateral THA groups.

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There were significant differences in the Six-Minute Walk Test and Stair Climb Test (Table 1). Pairwise comparisons revealed the posterior THA group had greater distances on the Six-Minute Walk Test (p=0.02, d=-0.97) and shorter times on the Stair Climb Test (p=0.04, d=0.93), representing better performance, than the lateral THA group. There were no significant group differences on the 30-Second Chair Stand Test.

Discussion

Few studies have compared muscle activation during gait between THA approaches. There were no differences in muscle activation between lateral and posterior THA groups. In comparison to healthy adults, the lateral THA group had higher gluteus medius activation and the posterior THA group had higher gluteus maximus and hamstring activation. Both THA groups did not demonstrate excessive pelvic drop or lateral trunk lean, which are indicators of Trendelenburg gait. THA groups had reduced hip flexion and adduction range of motion (i.e. excursion), but increased medial rotation range of motion, during gait compared to the healthy group. Therefore, abnormalities in muscle activation and hip angles remain 1 year post-THA, although there are few differences between posterior and lateral approaches.

Higher and prolonged gluteus medius activation was hypothesized in the lateral THA group, although the only statistically significant difference was in comparison to the healthy group. Likewise, previous studies demonstrated that patients that underwent lateral approach THA had elevated and prolonged gluteus medius activation during gait compared to healthy adults [14]. Higher gluteus medius activation in the lateral THA group is likely a compensation for muscle weakness, which was demonstrated by significantly lower isometric hip abduction torques. Despite these findings, the lateral THA group was able to control frontal plane pelvic obliquity and there were no signs of Trendelenburg gait (pelvic drop) or compensations for

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Trendelenburg gait (increased lateral trunk lean). The posterior THA group had higher gluteus maximus activation during loading response and elevated hamstring activation during midstance compared to the healthy group. This latter finding is supported by a previous study [15]. This is also likely a compensation for muscle weakness. The ANOVA demonstrated no statistically significant difference in isometric hip extension torque; however, the posterior THA group had lower values compared to the healthy group which represented a moderate effect (d=0.47). The posterior THA group also had higher isometric knee extension torque, which was likely due to a higher proportion of men. In summary, deficits in hip abductor and hip extensor muscles were present long-term in participants that had lateral or posterior THA approaches respectively. Long-term rehabilitation interventions, such as strengthening and functional exercises, should address these deficits.

The majority of joint angle differences were between THA and healthy groups, with few differences between posterior and lateral THA groups. Lower hip flexion and adduction angle excursions during gait in the THA groups is consistent with previous studies and is partly due to long standing joint restrictions from hip osteoarthritis [32,33]. Interestingly, medial rotation angle excursions were greater in the THA groups, especially the posterior THA group, which is supported and refuted by previous studies [34,35]. This might be a result of altered muscle activation of the deep rotators, which were not measured. In regards to pelvic obliquity, posterior THA group had lower range of motion during gait compared to the healthy group and there were no differences between approaches. Previous studies have found no differences in pelvic obliquity 1 year post-THA compared to healthy adults [32] and no differences between lateral and posterior THA approaches [5]. Finally, there were no group differences in the hip abduction moment, which is consistent with previous studies [9]. This moment provides an indication of the net muscular contributions of hip adductor and abductor muscles during gait. Along with the

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other kinematic and kinetic data, these findings indicate there is no evidence of Trendelenburg gait and hip abductors are providing sufficient force to control the pelvis in both THA groups.

For the HOOS, there were no significant differences between lateral and posterior THA groups. This is supported by a recent study that also compared these approaches 1 year post-THA [36]. However, the posterior THA group had better performance on the Six-Minute Walk Test and Stair Climb Test compared to the lateral THA group. A higher proportion of men in the posterior THA group likely explains this finding. As support, previous research demonstrates that men have better scores than women on similar clinical outcomes in both healthy populations and patients with hip osteoarthritis [37-39].

A study limitation is that pre-operative data were not available. Group differences could be partly due pre-operative disparities. Secondly, sex, age, weight, and height varied between groups, and these difference could impact gait [40]. Information about center of rotation restoration, offset, and component alignment were not available in the medical charts, and potential differences between THA groups could affect gait. Isometric muscle strength was measured in order to normalize EMG. A further long-term comparison of concentric and eccentric hip strength between THA approaches is required. Rehabilitation programs after the acute stages of recovery were not standardized and were not recorded. Finally, results cannot be generalized to other THA surgical approaches (e.g. direct anterior).

Conclusions

In conclusion, there were few differences in muscle activation and joint mechanics during gait between participants that had either lateral or posterior approaches for THA 1 year post-surgery. However, there were differences between both THA groups and healthy adults. The lateral THA group had elevated and prolonged gluteus medius activation during gait and isometric hip abduction weakness. Despite these findings, there was no evidence of excessive

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pelvic drop during gait. The posterior THA group had elevated and prolonged hip extensor activation during gait, which was likely a compensation for muscle weakness. Long-term strengthening and rehabilitation are required to address these muscular deficits.

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Table 1: Mean (standard deviation) values for demographic, spatiotemporal gait variables, and isometric torque values. Frequency is provided for sex.

Variable	Healthy (n=21)	Lateral THA (n=21)	Posterior THA (n=21)	p value*
Age (years)	63 (8)	68 (7)	62 (7)	0.05
Mass (kg)	71.95 (12.37)	73.72 (13.26)	82.97 (15.49)	0.03
Height (m)	1.65 (0.07)	1.66 (0.10)	1.72 (0.06)	0.01

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Body mass index (kg/m^2)	26.54 (4.82)	26.64 (3.16)	27.80 (4.54)	0.57
Sex (frequency)	15 women 6 men	11 women 10 men	6 women 15 men	-
Gait speed (m/s)	1.26 (0.14)	1.20 (0.18)	1.24 (0.19)	0.45
Gait stride length†	0.77 (0.08)	0.74 (0.07)	0.74 (0.07)	0.24
Gait stance time (% stride)	60.82 (1.31)	61.36 (1.78)	60.80 (1.30)	0.39
Hip abduction torque (Nm/kg)‡	1.25 (0.36)	1.00 (0.30)	1.13 (0.21)	0.04
Hip extension torque (Nm/kg)‡	1.26 (0.38)	1.17 (0.29)	1.12 (0.24)	0.31
Hip flexion torque (Nm/kg)‡	1.16 (0.26)	1.10 (0.21)	1.20 (0.25)	0.36
Knee extension torque (Nm/kg)‡	0.99 (0.27)	1.13 (0.27)	1.20 (0.23)	0.03
Knee flexion torque (Nm/kg)‡	0.71 (0.21)	0.61 (0.23)	0.75 (0.17)	0.06
HOOS-pain (/100)	98 (5)	92 (9)	96 (6)	0.07
HOOS-symptoms (/100)	95 (8)	92 (9)	92 (9)	0.35
HOOS-physical function (/100)	98 (4)	94 (7)	97 (5)	0.05
HOOS-sports (/100)	97 (9)	90 (13)	90 (11)	0.03
HOOS-quality of life (/100)	97 (6)	83 (16)	89 (14)	<0.01
Six-Minute Walk Test (m)	542.32 (90.71)	510.84 (64.19)	574.51 (67.66)	0.03
30-Second Chair Stand Test (reps)	16 (5)	15 (4)	18 (5)	0.09
Stair Climb Test (s)	8.94 (3.64)	10.36 (2.83)	8.03 (2.15)	0.04

THA=total hip arthroplasty; HOOS=Hip Disability and Osteoarthritis Outcome Score.
*p value from one-way analysis of variance or Kruskal-Wallis H Test (HOOS subscales).
†Stride length was normalized to height and has no units.
‡Isometric torque was not available for all exercises for one participant from the healthy group. One participant from the lateral THA group did not complete isometric hip abduction.

Table 2: Pairwise comparison for muscle activation principal component scores.

Muscle	PC	Healthy-Lateral THA		Healthy-Posterior THA		Lateral THA-Posterior THA	
		Mean difference (95% CI)	ES	Mean difference (95% CI)	ES	Mean difference (95% CI)	ES
Gluteus	1	-118.96	-0.97	-61.28	-0.63	57.67	0.50

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medius		(-207.00, -30.92)		(-149.33, 26.76)		(-28.14, 143.49)	
	2	-35.18 (-63.81, -6.56)	-0.95	-25.11 (-53.74, 3.52)	-0.70	10.07 (-17.83, 37.98)	0.27
	3	-6.87 (-32.21, 18.46)	-0.19	-11.40 (-36.74, 13.93)	-0.40	-4.53 (-29.23, 20.16)	-0.14
Gluteus maximus	1	-51.14 (-128.73, 26.44)	-0.60	-63.26 (-140.84, 14.32)	-0.58	-12.12 (-88.75, 64.51)	-0.11
	2	-8.56 (-37.00, 19.87)	-0.21	-31.76 (-60.19, -3.32)	-0.94	-23.19 (-51.28, 4.90)	-0.63
	3	-13.31 (-34.47, 7.85)	-0.49	-14.23 (-35.39, 6.93)	-0.58	-0.92 (-21.82, 19.98)	-0.03
Tensor fascia latae	1	-24.01 (-71.62, 23.60)	-0.37	-4.12 (-51.73, 43.49)	-0.07	19.89 (-27.72, 67.50)	0.30
	2	-6.67 (-28.20, 14.86)	-0.21	2.88 (-18.65, 24.41)	0.12	9.55 (-11.98, 31.08)	0.34
	3	-10.49 (-22.58, 1.60)	-0.58	-1.86 (-13.95, 10.23)	-0.14	8.63 (-3.46, 20.72)	0.53
Vastus lateralis	1	-0.90 (-56.57, 54.76)	-0.01	33.39 (-22.96, 89.75)	0.37	34.30 (-22.06, 90.65)	0.42
	2	-3.88 (-21.11, 13.36)	-0.14	2.98 (-14.47, 20.43)	0.10	6.86 (-10.59, 24.30)	0.25
	3	4.45 (-6.74, 15.65)	0.23	-3.01 (-14.34, 8.33)	-0.19	-7.46 (-18.80, 3.87)	-0.40
Vastus medialis	1	5.08 (-60.30, 70.46)	0.04	37.66 (-28.54, 103.85)	0.33	32.58 (-33.61, 98.77)	0.39
	2	-9.25 (-38.66, 20.16)	-0.17	-9.11 (-38.88, 20.67)	-0.18	0.14 (-29.63, 29.92)	0.00
	3	4.85 (-24.67, 34.38)	0.02	-10.72 (-40.67, 19.24)	-0.24	-15.57 (-46.25, 15.1)	-0.50
Rectus femoris	1	18.28 (-14.67, 51.23)	0.31	40.17 (6.81, 73.53)	0.74	21.89 (-11.47, 55.25)	0.47
	2	5.04 (-6.54, 16.62)	0.29	7.00 (-4.73, 18.72)	0.36	1.96 (-9.77, 13.68)	0.10
	3	6.80 (-1.78, 15.38)	0.30	6.41 (-2.29, 15.12)	0.42	-0.38 (-9.3, 8.53)	0.03
Lateral hamstrings	1	-24.73 (-60.32, 10.86)	-0.43	-18.74 (-54.32, 16.85)	-0.36	6.00 (-29.59, 41.58)	0.10
	2	10.27 (-6.02, 26.55)	0.40	29.15 (12.86, 45.43)	1.31	18.88 (2.60, 35.17)	0.61
	3	0.13 (-12.29, 12.55)	0.01	0.62 (-11.80, 13.04)	0.03	0.49 (-11.93, 12.91)	0.02
Medial hamstrings	1	-22.85 (-52.65, 6.95)	-0.44	-2.02 (-31.82, 27.78)	-0.05	20.83 (-8.97, 50.63)	0.41
	2	-0.36 (-19.10, 18.39)	-0.01	11.87 (-6.87, 30.62)	0.45	12.23 (-6.51, 30.98)	0.37
	3	-10.36 (-22.08, 1.36)	-0.55	-3.85 (-15.57, 7.86)	-0.20	6.51 (-5.21, 18.22)	0.34

Note: PC, principal component; CI, confidence interval; THA, total hip arthroplasty; ES, effect size

Table 3: Pairwise comparison for angle and moment principal component scores.

Angle/	PC	Healthy-	Healthy-	Lateral THA-

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Moment		Lateral THA		Posterior THA		Posterior THA	
		Mean difference (95% CI)	ES	Mean difference (95% CI)	ES	Mean difference (95% CI)	ES
Hip flexion angle	1	-12.60 (-68.51, 43.30)	-0.17	-42.03 (-97.94, 13.87)	-0.56	-29.43 (-85.33, 26.48)	-0.41
	2	18.39 (5.43, 31.35)	1.14	16.58 (3.62, 29.54)	0.93	-1.81 (-14.77, 11.15)	-0.11
	3	-1.77 (-9.40, 5.86)	-0.16	4.02 (-3.61, 11.65)	0.41	5.79 (-1.83, 13.42)	0.64
Hip adduction angle	1	-3.68 (-21.92, 14.55)	-0.15	2.04 (-16.20, 20.27)	0.09	5.72 (-12.51, 23.95)	0.24
	2	4.88 (-4.25, 14.01)	0.38	11.27 (2.14, 20.40)	0.89	6.39 (-2.73, 15.52)	0.62
	3	5.34 (-0.59, 11.27)	0.72	4.04 (-1.89, 9.96)	0.49	-1.31 (-7.23, 4.62)	-0.17
Hip medial rotation angle	1	12.33 (-39.81, 64.48)	0.17	-3.52 (-55.67, 48.63)	-0.05	-15.85 (-68.00, 36.30)	-0.23
	2	-15.42 (-28.18, -2.67)	-0.91	-17.87 (-30.63, -5.11)	-1.06	-2.44 (-15.20, 10.32)	-0.15
	3	-6.19 (-16.47, 4.09)	-0.49	-16.86 (-27.14, -6.58)	-1.20	-10.67 (-20.95, -0.39)	-0.77
Pelvic obliquity angle	1	8.02 (-4.86, 20.89)	0.44	0.79 (-12.09, 13.66)	0.04	-7.23 (-20.11, 5.64)	-0.49
	2	4.73 (-0.99, 10.45)	0.59	3.66 (-2.06, 9.38)	0.54	-1.08 (-6.80, 4.65)	-0.14
	3	3.75 (-1.12, 8.63)	0.57	5.63 (0.75, 10.50)	0.85	1.87 (-3.01, 6.75)	0.31
Lateral trunk lean angle	1	-10.84 (-23.86, 2.18)	-0.65	-11.29 (-24.31, 1.73)	-0.66	-0.45 (-13.47, 12.57)	-0.03
	2	-3.07 (-6.93, 0.80)	-0.55	-1.43 (-5.30, 2.43)	-0.28	1.63 (-2.23, 5.50)	0.36
	3	-1.04 (-4.08, 1.99)	-0.28	-0.56 (-3.60, 2.47)	-0.14	0.48 (-2.56, 3.51)	0.12
Hip extension moment	1	0.20 (-0.62, 1.03)	0.22	0.31 (-0.52, 1.13)	0.27	0.10 (-0.72, 0.93)	0.09
	2	-0.04 (-0.56, 0.49)	-0.06	-0.09 (-0.61, 0.43)	-0.13	-0.06 (-0.58, 0.47)	-0.07
	3	-0.01 (-0.26, 0.24)	-0.03	0.01 (-0.24, 0.26)	0.03	0.02 (-0.23, 0.27)	0.06
Hip abduction moment	1	-0.09 (-0.74, 0.55)	-0.11	-0.14 (-0.79, 0.51)	-0.15	-0.05 (-0.70, 0.60)	-0.06
	2	0.31 (-0.06, 0.68)	0.65	0.15 (-0.22, 0.52)	0.32	-0.16 (-0.53, 0.21)	-0.31
	3	-0.06 (-0.34, 0.23)	0.72	0.07 (-0.22, 0.35)	0.49	0.12 (-0.16, 0.41)	-0.17
Hip medial rotation moment	1	-0.07 (-0.28, 0.15)	-0.21	-0.14 (-0.35, 0.07)	-0.57	-0.07 (-0.29, 0.14)	-0.27
	2	0.06 (-0.07, 0.18)	0.39	0.02 (-0.10, 0.15)	0.14	-0.04 (-0.16, 0.09)	-0.21
	3	-0.01 (-0.07, 0.06)	-0.09	-0.01 (-0.07, 0.05)	-0.13	-0.00 (-0.07, 0.06)	-0.05

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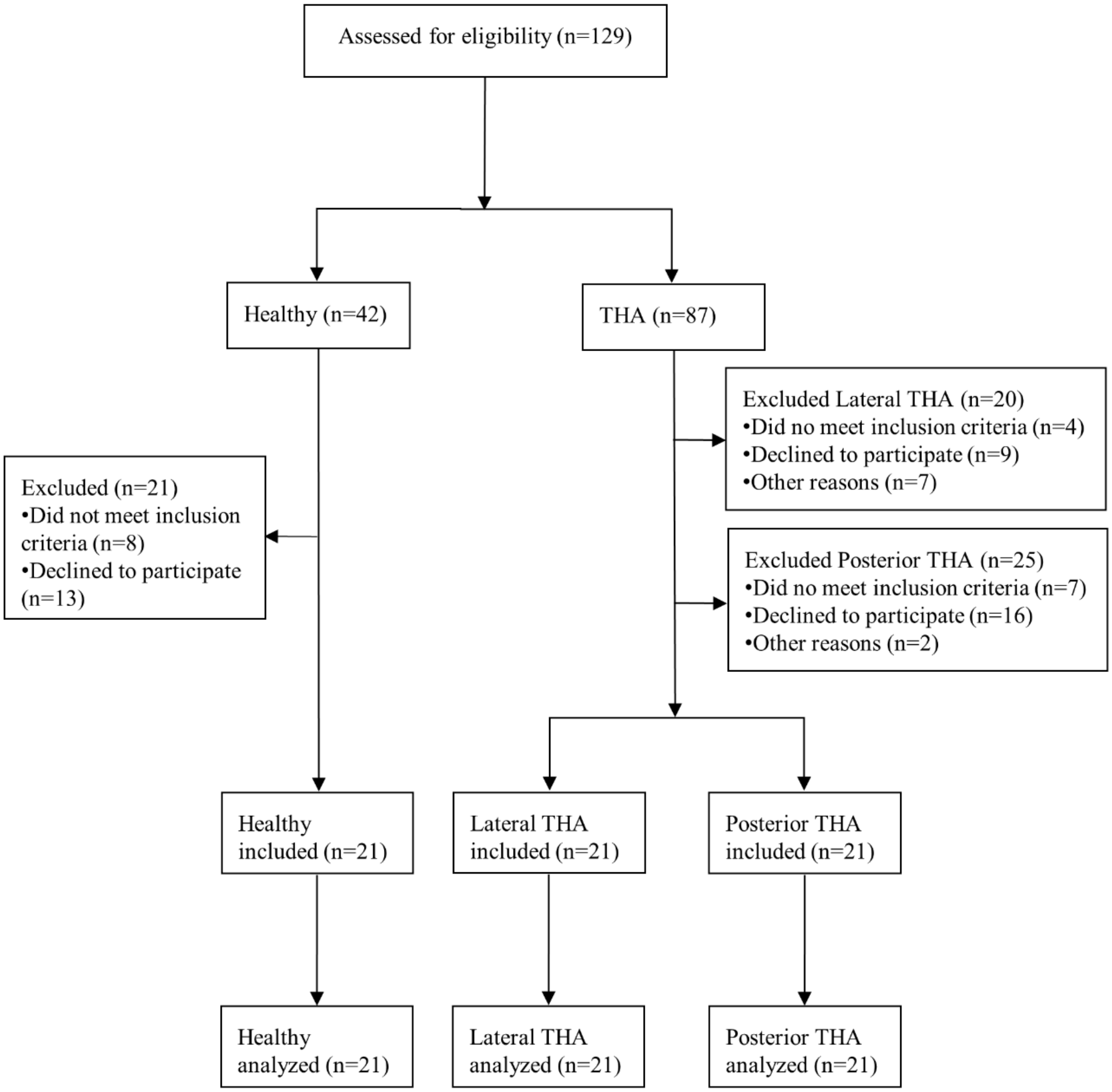

Figure 1: Flow diagram of steps involved in the screening and enrollment of the healthy and total hip arthroplasty (THA) groups.

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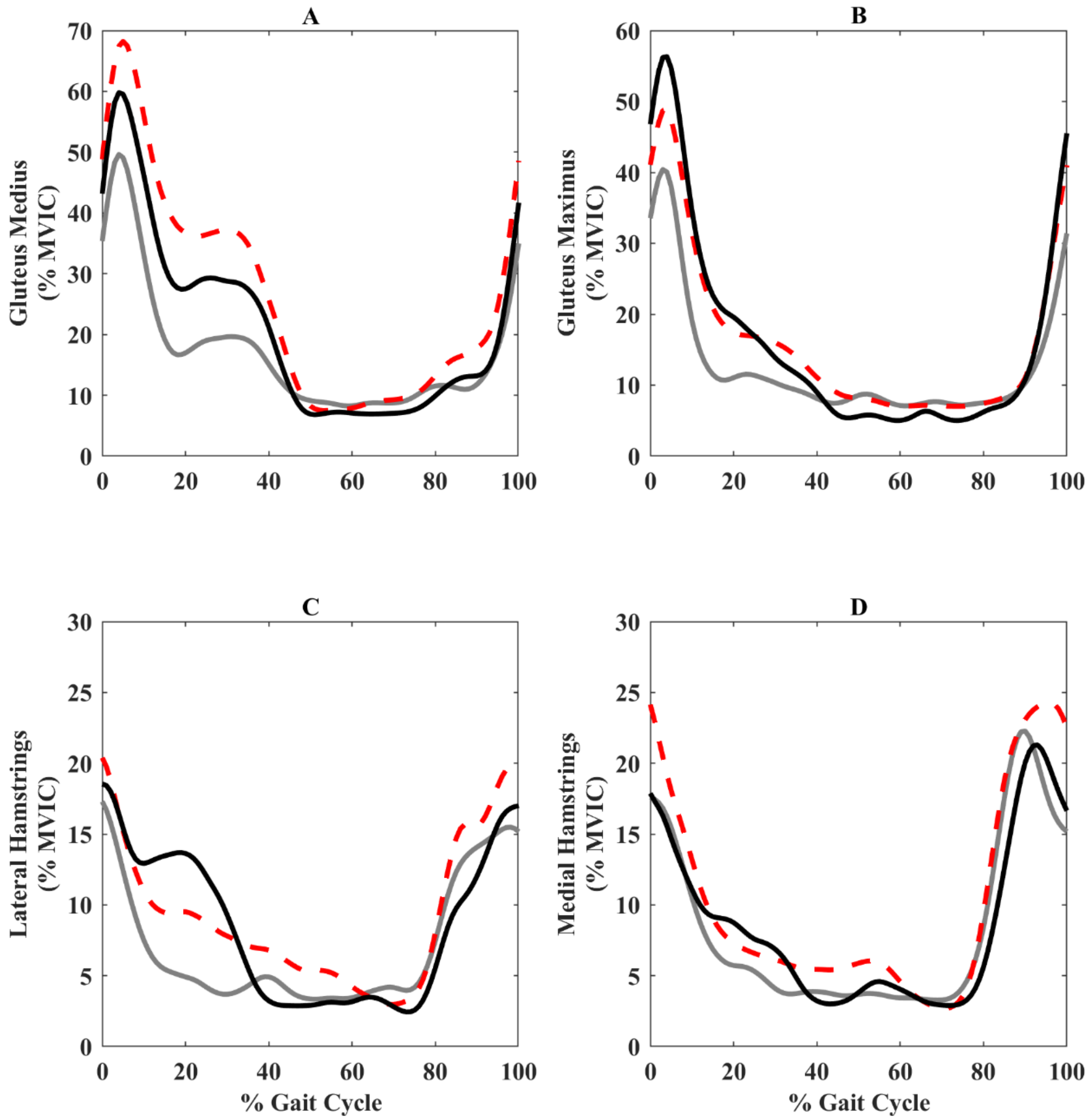

Figure 2. Muscle activation during gait. Gluteus medius (A), gluteus maximus (B), lateral hamstring (C), and medial hamstring (D) electromyography, normalized to maximum voluntary isometric contraction (MVIC), for the lateral THA (red, dashed lines), posterior THA (black, solid lines), and healthy (grey, solid lines) groups.

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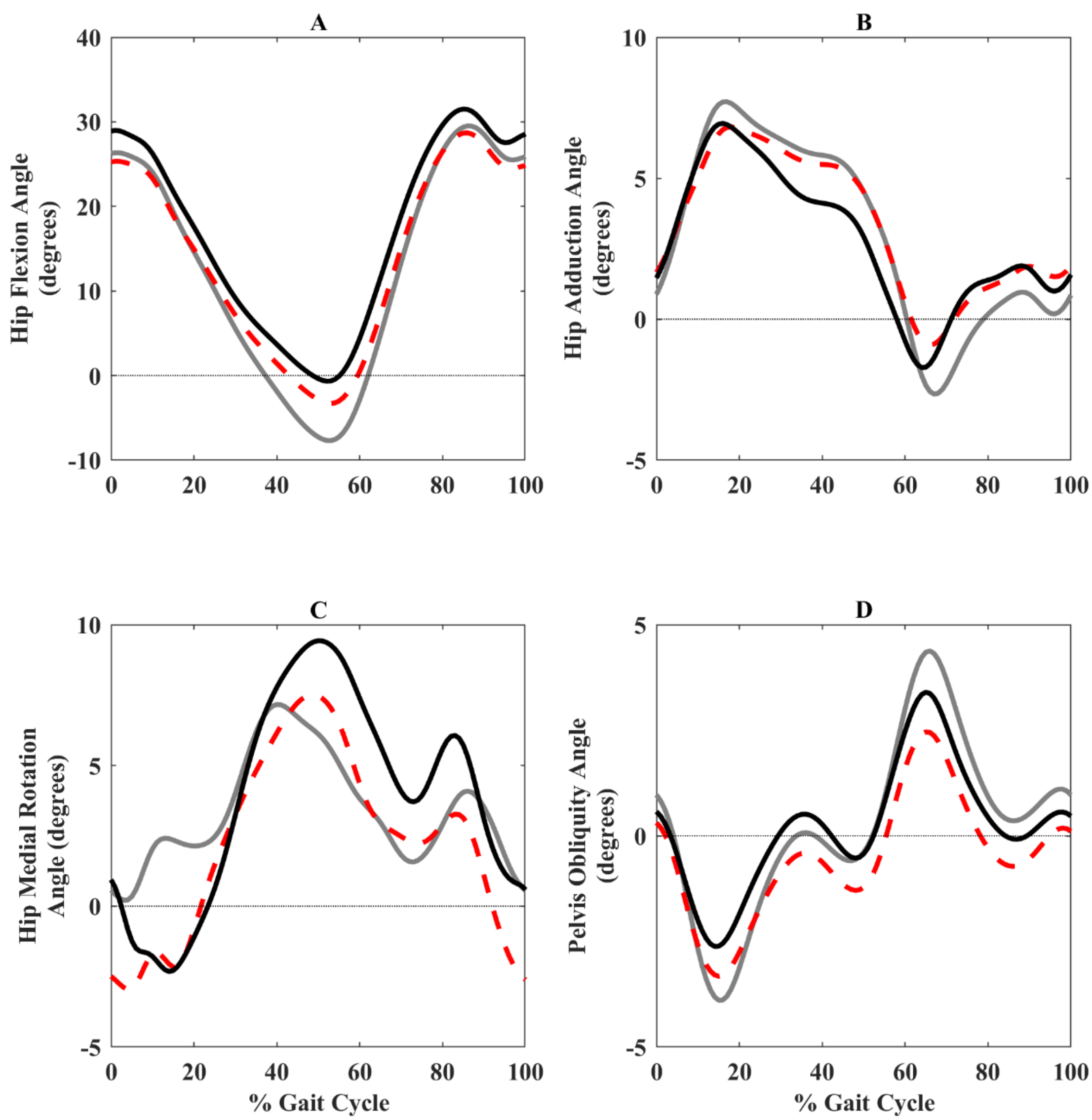

Figure 3. Hip and pelvis angles during gait. Hip flexion (A), hip adduction (B), hip medial rotation (C), and pelvic obliquity (D) angles for the lateral THA (red, dashed lines), posterior THA (black, solid lines), and healthy (grey, solid lines) groups. Positive values are represented by hip flexion, hip adduction, hip medial rotation, and ipsilateral pelvic drop.

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