Preoperative Factors Associated with Postoperative Gait Kinematics and Kinetics after Total Hip Arthroplasty

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Abstract

Objective: To determine how patient factors: age, sex, body mass index (BMI), clinical scores and physical exam findings, are associated with gait recovery after total hip arthroplasty (THA).

Method: 145 subjects, who were evaluated with standard gait analysis, the Harris Hip Score (HHS), and a physical exam including passive range of motion, hip abductor strength assessment, before and after primary unilateral THA, were identified from an IRB-approved repository. Sagittal plane dynamic range of motion (ROM) and 3D peak external moments were averaged from operated-side normal-speed trials at each visit. We used linear regression analysis to evaluate the association among preoperative clinical factors and postoperative gait, with and without controlling for the influence of preoperative gait variables.

Results: Sagittal and transverse plane moments, and the peak abduction moment seen in early stance, significantly improved after THA ($p<0.001$, effect size $d = 0.22$-1.04). The peak adduction moment did not change significantly ($p=0.646$), although the change ranged from -2.7 to + 4.0 %Body weight x height (-80% to +315%). Preoperative gait, clinical factors and patient characteristics predicted up to 33% of the variability in postoperative gait. Notably, greater preoperative abductor strength was associated with higher postoperative adduction and external rotation moments ($R=0.197$-0.266, $p<0.05$) after adjusting for age, sex, BMI and preoperative gait.

Conclusion: Preoperative clinical factors predicted several specific aspects of objectively-characterized postoperative gait function. Physical exam findings can augment the predictive ability of clinical outcome measures, and potentially help guide rehabilitation plans.

Keywords: total hip arthroplasty; functional recovery; gait; biomechanics; outcome measures

Introduction

Across patient populations, countries, and evaluation methods, between 14 and 46% of patients report functional limitations or insufficient functional improvement after total hip arthroplasty (THA).[1-4] For example, 22% of 5707 THA patients from the Mayo Clinic Total Joint Registry surveyed 2 years after surgery reported "moderate" walking limitations and 6% reported "severe" walking limitations (with options including none, mild, moderate, and severe).[4] These statistics are particularly disappointing because of the high value that patients place on functional recovery.[5, 6] Identifying new strategies to improve postoperative function is an important clinical and research priority.

Walking is the aspect of function in which THA candidates most desire or expect improvement.[6, 7] Moreover, normal gait may promote an implant loading environment that reduces the likelihood of implant wear or dislocation. Quantitative gait analysis can precisely and objectively characterize specific aspects of walking. [8-12] Joint motions and external moments can be calculated from the positions of reflective markers on body segments and ground reaction forces recorded during walking. External moments must be balanced by internal moments produced by the muscles and other joint structures. So, for example, when we measure an external hip adduction moment, we can infer net activity of the hip abductors. Many studies have described postoperative THA gait. [13-17] These studies, however, have generalizability concerns that limit how they can be used and interpreted to inform rehabilitation practices. First, we know from the clinical literature that preoperative function is an important determinant of postoperative function;[3, 18] unfortunately, a recent meta-analysis points out that most gait analysis studies have not included a preoperative evaluation.[16, 17] Second, many gait analysis studies have had relatively small sample sizes – in the same meta-analysis, all but one study had fewer than

30 subjects. Finally, most studies are limited to a single or a small number of implant designs, surgeons, and surgical approaches. Results from gait analysis studies could help inform the direction of rehabilitation and our understanding of THA function, but a fuller understanding of the influence of preoperative factors on changes in gait after THA, in a heterogeneous population is needed.

The goal of this study was to test the association between preoperative clinical findings and gait improvement in a relatively large, heterogeneous group of subjects who participated in longitudinal gait analysis studies before and after primary unilateral THA. Subjects were heterogeneous with respect to surgeon and surgical approach, implant type, and other aspects of clinical management, but had participated in gait analysis studies that had similar inclusion criteria and study designs. The objective of this investigation was to determine whether any self-reported clinical outcome measures (e.g. pain) or exam findings (e.g. passive range of motion) were associated with postoperative gait after THA, taking preoperative gait into account. The broader rationale for this study was that preoperative clinical findings associated with larger increases in the selected gait variables – with the assumption that higher, i.e. closer to normal values are preferable – could potentially be used to identify specific aspects of function that should be targeted in postoperative rehabilitation or to help screen subjects for investigations of new rehabilitation interventions.

Methods

Subjects

Subjects were identified using an IRB-approved repository, containing gait analysis data, demographic data, and clinical scores for subjects tested before and after primary unilateral

THA. All subjects gave written informed consent for the studies in which they were enrolled and for their data to be included in the repository. Use of the repository for the present analysis was also IRB-approved. The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. All subjects had been recruited for observational studies of gait mechanics or implant loading before and/or after THA. Subjects meeting inclusion criteria were sequentially enrolled from the surgeons' practices, in two large high-volume urban medical centers. The primary inclusion criterion for the original studies was candidacy for primary unilateral THA. Most studies specifically required a diagnosis of osteoarthritis; all excluded patients with inflammatory arthritis and trauma. Other exclusion criteria included self-reported pain, past or anticipated surgical procedures, or any previous diagnoses involving lower extremity joints other than the affected hip. None of the original studies restricted subject age, clinical or radiographic disease severity. One of the original studies specifically involved minimally invasive surgical approaches. Otherwise, patient selection, surgical approach, and perioperative management were per surgeons' (and rehabilitation providers) usual protocols, and were not dictated by the design of the original studies. Some original study results have been previously published.[10, 13, 15]

We sought subjects with a preoperative evaluation and a postoperative evaluation that was conducted at least 6 months after surgery. Subjects were not considered if no preoperative evaluation was available in the repository. If a subject had been evaluated more than once after surgery, the visit closest to the one year postoperative time point was selected. (No subjects were evaluated more than once before surgery.) The one-year time point was selected because it was the most commonly tested time-point in the subject group considered, because our previous work has suggested that gait stabilizes by this time after surgery,[15] and because this is a commonly used time-point in the literature.[16]

Preoperative Clinical Assessment

Preoperative clinical status was summarized using the Harris Hip Score (HHS)[19] and an in-house assessment form administered at the time of the gait evaluation. Although the HHS was not originally developed for modern THA, it is still widely used in orthopedic surgery and has good validity and reliability in evaluation of THA patients.[20] It includes domains of pain, gait function, activities of daily living (ADLs), absence of "deformity," and an assessment of passive range of motion. . Scores range from 0 to 100 (best). In this study, the total preoperative HHS as well as the HHS pain, gait, and ADL subscores were analyzed. Passive range of motion in flexion, adduction, abduction, internal rotation, and external rotation were assessed. Hip abductor strength was assessed by manual muscle testing on a 5 point scale,[21] where 0 represents the inability to abduct the hip, and 5 represents the ability to resist both gravity and manual resistance. Finally, subjects were questioned about other problematic joints with an open-ended list of questions beginning "Do you have any problems with your …." and ending with contralateral hip, ipsilateral knee, contralateral knee, low back, upper extremities, and other (e.g. cervical spine). We tallied the number of affirmative responses, and used this number as an additional preoperative clinical measure for the analysis.

Gait Analysis

All subjects underwent gait analysis using the same standard methods that have been previously described in the literature.[22, 23] Briefly, retro-reflective markers were placed on lower extremity bony landmarks. Joint centers were located based on the position of these markers, and anthropometric measurements. An optoelectronic camera system (Qualisys North America, Deerfield, IL) and multicomponent force plate (Bertec, Columbus, OH) recorded marker positions and ground reaction forces as subjects walked at a range of self-selected speeds (slow, normal, fast). The sagittal plane dynamic range of motion of the hips, knees, and ankles were calculated from marker positions. Inverse dynamics were used to compute external moments about each joint in the sagittal, frontal, and transverse planes. Moments were normalized to subject body weight and height (%BWxHt). This normalization technique reduces the differences between men and women that are solely attributable to body size.[24] The gait variables of interest here were the sagittal plane dynamic range of motion and peak external moments in the sagittal, frontal, and transverse planes, for the operated hip (Figure 1), averaged from trials collected at each subject's self-selected normal walking speed.

Statistical Analysis

To understand the association between preoperative gait and clinical variables and postoperative gait, we used t-tests, Pearson correlations, and linear regression analysis. First, paired Student's *t*-tests were used to assess pre- to postoperative change in gait variables without considering the potential influence of the other variables. Next, Pearson correlations were used to to assess the unadjusted association between each preoperative clinical variable and the pre-to-postoperative change in each gait variable. Next, second order correlations were calculated to evaluate these associations accounting for potential influence of the preoperative value of each gait variable, and finally, to evaluate these associations statistically accounting for potential influence of preoperative gait variables, as well as age, sex, and BMI. Finally, we used regression analysis to identify a set of preoperative variables associated with each postoperative gait variable. To avoid introducing bias due to the relationships among the potential covariates, variable selection was conducted using the directed acyclic graphic approach.[25] The preoperative candidate variables considered in the subsequent regression procedures were the HHS, the HHS pain, gait function, and ADL function subscales, degree of flexion contracture, and the respective preoperative gait variable. Data were missing for some of the potential preoperative variables. Forward and backward selection procedures were applied first on the subset with no missing data and again with the largest available sample for the subset of selected variables. We reported the coefficients with 95% confidence intervals, and adjusted R^2 values for the best models for each gait variable.

Results

Subjects

145 subjects were identified from the data repository (Figure 2). Surgeries were conducted at two large urban medical centers by 8 different surgeons. Subjects were initially enrolled under 4 related study protocols. Physical and clinical characteristics were gathered for all subjects (Table 1) and compared for the subjects grouped either by original study enrollment or surgeon. There were no statistically significant differences in age, sex, or BMI among subjects when grouped by original study enrollment ($p = 0.187$ to 0.475) or surgeon ($p = 0.052$ to 0.475).

Gait improvement – unadjusted

Based on paired *t*-tests, there were statistically significant improvements in all gait variables ($p < 0.001$) except the peak hip adduction moment (Table 2). Effect sizes for improvements in sagittal and transverse plane gait variables were medium to large.[26, 27] Effect sizes were small for frontal plane improvements.

Association between self-reported clinical variables and postoperative gait changes

The Harris Hip Score and its subscales predicted changes in several gait variables (Table 3). Subjects with higher HHS values before surgery had lower postoperative values of the peak hip adduction and external rotation moments, after adjusting for age, sex, BMI, and the preoperative values of the respective gait variables. Identical relationships were seen with the HHS ADL function subscale. Preoperative pain was inversely correlated with the postoperative peak abduction moment, after adjusting age, sex, BMI, and preoperative abduction moments. Number of other troubling joints was not associated with changes in gait variables ($p = 0.060$ to $p = 0.970$).

Association between physical exam derived clinical variables and postoperative gait changes

Passive range of motion (Table 4) and manually tested hip abductor strength (Table 5) also predicted changes in several gait variables. After adjusting for age, sex, and preoperative gait variables, passive flexion range of motion was inversely correlated with the peak hip flexion moment. Passive hip external rotation range of motion was positively correlated with the peak extension moment and inversely correlated with the peak external rotation moment. Higher preoperative abductor strength was independently associated with greater postoperative hip adduction and external rotation moments, and lower abduction moments.

Regression models

Combinations of preoperative variables predicted 15-33% of the variation in postoperative gait (Table 6). As expected, higher values of preoperative gait variables were associated with higher values of the same variables after surgery. In fact, the preoperative values of the hip range of motion, and peak moments in the sagittal and transverse planes were the only statistically significant explanatory variables that remained in the respective regression models. In the frontal plane, the postoperative peak adduction moment was associated with its respective preoperative value, as well as the preoperative HHS ADL subscale. Based on the magnitude of the standardized regression coefficients, however the preoperative adduction moment was approximately twice as influential as the HHS ADL subscale in determining the postoperative adduction moment. Along with the preoperative peak abduction moment, HHS, HHS pain and HHS gait function subscales were associated with postoperative abduction moments.

Discussion

This study was motivated by the need for better ways to predict overall functional improvement after THA. We used quantitative gait analysis to characterize function, rather than PROs, because of the direct link between gait analysis findings and the actions of specific muscle groups. Most previous studies using PROs find that THA patients who have higher preoperative pain or function scores on PROs have higher postoperative scores but less relative improvement.[1, 3, 4, 28, 29] However it is not clear how much of this phenomenon is attributable to the fact that patients with a high preoperative PRO scores have less room for improvement in these same scores. In this study, by using gait analysis to characterize function, we could assess the association of preoperative clinical status and postoperative function independent of PRO measurement properties. We also assessed whether or not any physical exam measures were associated with gait changes after THA. We found several meaningful associations between preoperative clinical findings and specific aspects of postoperative gait that could potentially be used to inform new rehabilitation strategies.

Higher preoperative HHS, as well as higher scores on the HHS ADL function subscale, were associated with lower postoperative hip adduction and external rotation moments. The hip adduction moment reflects net activity of the hip abductor muscles, which include the gluteus medius, gluteus minimus, and tensor fascia latae. In addition to maintaining pelvic stability in the frontal plane during single limb stance, these muscles perform internal hip rotation and provide stability in the transverse plane during walking.[30-33] Accordingly, we interpret both the peak adduction and external rotation moments as a reflection of net activity of the hip abductors during walking. Thus, patients with better clinical scores before surgery actually had less improvement in abductor function. We note that there was no correlation between the preoperative hip adduction moment and either the total HHS or the HHS ADL subscore ($R = 0.055$, $p = 0.488$ and $R = 0.038$, $p = 0.619$). Thus, this finding does not indicate that subjects with better preoperative HHS simply had better preoperative abductor function. One possibility is that patients with higher pre- or postoperative HHS might have received less intensive focus on the hip abductors during their postoperative physical therapy because their deficits were less apparent or were not perceived as being problematic.

Many studies have found that the peak hip adduction moment or external rotation moments in postoperative THA patients is lower than in control subjects.[16, 17] Lateral and anterior surgical approaches are often associated with poorer abductor function compared to posterior approaches in many,[34-36] but not all studies.[37-39] A recent study by Queen et al., failed to identify superior gait outcomes in subjects who underwent THA with posterior approaches compared to lateral approaches by one year after surgery.[39] They noted, however, that preoperative HHS were higher in the posterior group than in the other groups. Based on our finding that preoperative HHS are associated with some lower postoperative gait moments, we can speculate that Queen's study would have found superior gait outcomes in the posterior group had their preoperative scores been comparable to the other groups. As with our study, it is possible that their subjects who were perceived as more highly functioning received less intensive rehabilitation. In any case, our study indicates that preoperative clinical status should be taken into account when evaluating different surgical approaches or other types of interventions, and emphasizes the need for perioperative screening for rehabilitation planning.[40]

Subjects with more abductor strength before surgery had higher postoperative peak adduction and external rotation moments after surgery. Preoperative abductor strength was associated with the preoperative values of these moments (respectively $R = 0.203$, $p = 0.026$ and $R = 0.260$, $p = 0.004$). This suggests that hip abductor weakness assessed before surgery may indicate a need for special focus on dynamic abductor function after surgery, especially in those patients with incongruously high self-reported functional scores. Although causality cannot be inferred from this study design, this study also supports the concept that preoperative abductor strengthening could improve postoperative gait function. So far, most preoperative exercise interventions do not specifically target this muscle group,[41-43] and so far, while they are effective in the preoperative and early postoperative period, none appear to have lasting benefits. We can speculate from this work, that earlier (i.e. preoperative), more specific, or more sustained, emphasis on the hip abductors in particular could lead to further benefit. It is also important to note that the hip adduction moment is not a direct reflection of abductor strength, and that stronger hip abductors would not necessarily result in more normal hip adduction moments. Trunk position, mechanical alignment of the limb, and reconstructed joint geometry, among other factors, all help determine frontal plane hip loading during gait.

The associations between passive range of motion and gait changes were somewhat surprising because the peak gait variables do not necessarily occur at the extremes of hip motion. Subjects with more range of motion in external rotation before surgery had higher peak extension moments after surgery. The peak extension moment reflects net activity of (or demand on) hip flexors. Several studies have found that this moment is reduced compared to control subjects after surgery.[13, 14, 16] The peak extension moment occurs toward the end of stance when the hip is slightly extended. Others have found that hip extension in late stance is typically reduced compared to healthy controls.[14, 16] Thus it is possible that being able to achieve sufficient hip extension, and moreover to achieve some external rotation of the hip with this hip extension would give the hip flexors a more mechanically advantageous position, or allow muscles that can have hip flexion as a secondary role to participate in this action (e.g. the anterior fibers of the gluteus medius). Expanding the hip range of motion in external rotation may not be emphasized after surgery, so preoperative motion restrictions would likely persist. Unfortunately no transverse plane kinematics were collected and electromyography was not conducted so these speculations cannot be evaluated with the information available. Preoperative range of motion in flexion was inversely correlated with the postoperative peak external rotation moment. A related variable, the degree of hip flexion contracture was included in the regression model, however the coefficient was not statistically significant at the $p<0.05$ level. This casts doubt on the importance of this variable. We do know from recent work,[44] that better hip range of motion is associated with better clinical scores. In some older adult populations, reduced hip range of motion may be associated with increased fall risk as well.[45] Thus, improving hip range of motion is potentially important for THA patients for other reasons.

Even though other significant joint disease was an exclusion criterion for enrollment into the original studies, only 52 of the 167 subjects who answered this question reported having no other troubling joints. Number of other troubling joints was not associated with any postoperative gait variable. This is in contrast to findings of several recent studies, that having a higher number of other troublesome joints was associated with poorer functional outcomes in hip and knee arthroplasty patients.[3, 18, 46] It is possible that limitations arising from joints other than the affected hip do not affect objectively-measured hip function, but do affect the patient's perception of function.

Lower BMI was associated with higher postoperative values of range of motion, adduction moments, and external rotation moments. This is in line with findings that lower BMI is associated with better self-reported functional scores in THA patients.[2, 47] However, these studies also show that patients with higher BMIs achieve more relative improvement in function and emphasize that even people with very high BMIs achieve considerable benefit from THA. Nevertheless, this study supports the idea that reducing BMI may be an important part of an overall preoperative strategy to optimize surgical outcomes.

This study had several strengths including a large sample size (relative to other gait analysis studies), the inclusion of preoperative gait data, and the inclusion of both self-reported measures and information taken from physical exam. There were of course, several unavoidable limitations that, while unlikely to change the conclusions, may influence generalizability and future research directions. First, the pooling of data from several studies means that numerous examiners were involved in evaluating these subjects. Although training and methods are standardized, inter-rater variability is a potential issue. The number of testers may also have impacted the amount of available data, as a few testers may not have fully completed the HHS form. Next, several factors not considered in this study can have a large influence on gait biomechanics after THA. Postoperative joint geometry reconstruction can be an important contributor to hip joint loading during gait,[48] hip abductor strength,[49, 50] and has recently been linked to clinical outcomes.[29] The influence of femoral head size on gait has also been investigated.[51] Unfortunately radiographs were not available for all subjects, so we could not evaluate the influence of these factors on gait in this study. Next, individual surgeons may have different thresholds for how low clinical scores should be before THA is considered. In these subjects, however, preoperative HHS did not differ when subjects were grouped by surgeon (independent-samples Kruskal-Wallis $p = 0.070$), when subjects from the most active surgeon ($n = 83$) were compared to those from all other surgeons together (Mann-Whitney $p = 0.067$) or when the subjects from the two most active surgeons were compared (Mann-Whitney $p = 0.950$). Thus, individual trends in patient selection among surgeons are unlikely to have substantially influenced these results. Finally, surgical approach,[15, 35, 39, 52] and variability in rehabilitation programs [53-56] could potentially have an influence on gait outcomes. So far, most studies show that few differences are present, particularly with longer follow-up times.[15, 35, 39, 52, 57, 58] however, a recent meta-analysis found a statistically significant advantage of posterior approaches over lateral approaches regarding the Trendelenburg sign or gait, which indicate poor abductor strength.[34] Although the lack of information on surgical approach in particular is a major limitation of this study, the heterogeneity in this sample may be viewed as strength because it means the study findings are more likely to be generalizable.

In conclusion, preoperative clinical status, as assessed through the HHS and physical exam, can predict several aspects of postoperative gait changes. Notably, this study was to our knowledge the first to demonstrate a link between preoperative hip abductor strength and postoperative dynamic abductor function. This work has implications for the ongoing efforts to improve functional outcomes for THA patients. First, while Westby and colleagues reported expert consensus recommendations for preoperative screening for clinical rehabilitation planning using PROs,[40] this study suggests that physical exam measures such as manual muscle strength could enhance preoperative planning. Where available, preoperative gait analysis could play a role as well. A greater understanding of preoperative factors related to postoperative gait mechanics could help surgeons and patients refine their expectations for postoperative function. This is important because patient expectations are an important independent determinant of outcomes.[7, 59] Also, patients who may be risk for poor postoperative abductor function, based on preoperative factors identified here, might be advised to undergo THA with surgical approaches associated with better abductor outcomes. Finally, although prospective studies are needed to establish causality, this study suggests that improving preoperative abductor strength and range of motion could be a useful strategy to increase the likelihood of good gait function after surgery. Interventions that improve gait function via trunk position modification, feedback to improve gait symmetry,[60] or other gait retraining modifications,[61] may help improve THA outcomes.

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Center, Joan and Paul Rubschlager Motion Analysis Laboratory.

Contributions

Dr. Foucher was responsible for study design and conception, data analysis and interpretation, drafting the article, and preparing the manuscript for submission. Dr. Freels provided statistical expertise, participated in data analysis and interpretation, and critical revision of the article for important intellectual content. Dr. Foucher (kfouch1@uic.edu) takes responsible for the integrity of the work as a whole.

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The study sponsors had no role in the study design, data collection, analysis, or interpretation, or manuscript preparation.

Competing interest statement

The authors deny any financial or personal relationships that could inappropriately influence the work.

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Table 1. Physical and clinical characteristics of the study subjects (66 men, 65 women).

	Mean (SD)	Median	Min	Max
Age (years)	61 (10)	62	27	85
Height (m)	1.7 (0.1)	1.7	1.5	1.9
Weight (kg)	84 (18)	81	51	144
BMI (kg/m^2)	28 (5)	28	19	48
Time between preoperative evaluation and surgery (weeks)	2.7 (2.6)	2	0	15
Follow-up time (months)	14 (4)	13	6	37
Preoperative HHS	57 (14)	52	32	89
Postoperative HHS*	92 (11)	96	46	100
Change in HHS	35 (16)†	37	-10	65
Preoperative Diagnosis	Osteoarthritis or Degenerative Joint Disease (n = 123) Avascular Necrosis (n = 4) Ankylosing Spondylitis (n = 1) Not listed (n = 17)			

*Postoperative HHS were available for 126 subjects. As a group these subjects had excellent clinical outcomes.
†Change represents statistically significant improvement ($p < 0.001$).

Table 2. Sagittal plane dynamic hip range of motion (in degrees) and peak external moments (in %Body Weight x Height) during level walking at preferred speeds, for subjects (n = 145) before and ~1 year after primary unilateral total hip arthroplasty. Paired *t*-tests indicate substantial improvement in most gait variables, without adjusting for sex and preoperative clinical status. With the exception of frontal plane moments, improvements had medium to large effect sizes.

	Preoperative Value Mean ± SD	Postoperative Value Mean ± SD	Mean difference ± SD (95% CI)	p value	Effect Size
Sagittal Plane Dynamic Hip Range of Motion	16.3 ± 6.0	25.5 ± 6.0	9.2 ± 5.8 (8.2, 10.2)	< 0.001	1.6
Peak Flexion Moment	4.2 ± 1.5	5.9 ± 1.9	1.7 ±1.7 (1.4, 2.0)	< 0.001	1.0
Peak Extension Moment	1.8 ± 0.8	2.8 ± 1.1	0.9 ± 1.1 (0.8, 1.1)	< 0.001	0.81
Peak Adduction Moment	3.4 ± 1.1	3.4 ± 1.0	0.04 ± 1.1 (0.15, 0.24)	0.646	0.04
Peak Abduction Moment	1.6 ± 0.8	1.8 ± 0.9	0.3 ± 0.8 (0.12, 0.39)	< 0.001	0.38
Peak External Rotation Moment	0.3 ± 0.2	0.4 ± 0.2	0.1 ± 0.2 (0.1, 0.13)	< 0.001	0.50
Peak Internal Rotation Moment	0.4 ± 0.2	0.5 ± 0.2	0.1 ± 0.2 (0.11, 0.17)	< 0.001	0.50

Table 3. Associations between postoperative gait variables and the Harris Hip Score (HHS), self-reported HHS subscales. Shaded boxes highlight $p < 0.05$.

	Harris Hip Score (HHS)			HHS pain			HHS gait function			HHS ADL function		
	Unadjusted	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]
Sagittal Plane Hip Range of Motion	R = 0.160 p = 0.066	R = -0.014 p = 0.872	R = 0.066 p = 0.458	R = 0.001 p = 0.986	R = -0.061 p = 0.470	R = 0.038 p = 0.653	R = 0.121 p = 0.148	R = -0.044 p = 0.600	R = -0.001 p = 0.993	R = 0.173 p = 0.038	R = 0.071 p = 0.396	R = 0.069 p = 0.413
Peak Flexion Moment	R = 0.152 p = 0.081	R = 0.027 p = 0.756	R = 0.476 p = 0.978	R = 0.030 p = 0.720	R = -0.035 p = 0.681	R = -0.066 p = 0.435	R = 0.168 p = 0.043	R = 0.002 p = 0.983	R = -0.022 p = 0.792	R = 0.007 p = 0.931	R = -0.023 p = 0.789	R = -0.043 p = 0.609
Peak Extension Moment	R = 0.111 p = 0.202	R = 0.005 p = 0.956	R = 0.007 p = 0.935	R = 0.092 p = 0.271	R = 0.044 p = 0.602	R = 0.074 p = 0.386	R = 0.129 p = 0.121	R = -0.019 p = 0.821	R = -0.027 p = 0.752	R = 0.055 p = 0.514	R = -0.041 p = 0.629	R = -0.061 p = 0.475
Peak Adduction Moment	R = -0.128 p = 0.141	R = -0.159 p = 0.069	R = -0.195 p = 0.027	R = -0.126 p = 0.132	R = -0.102 p = 0.222	R = -0.111 p = 0.191	R = 0.031 p = 0.709	R = -0.018 p = 0.829	R = -0.041 p = 0.626	R = -0.160 p = 0.055	R = -0.186 p = 0.026	R = -0.235 p = 0.005
Peak Abduction Moment	R = 0.114 p = 0.191	R = -0.030 p = 0.734	R = -0.042 p = 0.634	R = -0.066 p = 0.429	R = -0.159 p = 0.057	R = -0.191 p = 0.023	R = 0.142 p = 0.089	R = -0.045 p = 0.592	R = -0.039 p = 0.643	R = 0.062 p = 0.455	R = -0.056 p = 0.504	R = -0.059 p = 0.485
Peak Internal Rotation Moment	R = 0.142 p = 0.104	R = 0.077 p = 0.382	R = 0.042 p = 0.633	R = 0.0001 p = 0.999	R = -0.033 p = 0.976	R = -0.012 p = 0.885	R = 0.279 p = 0.001	R = 0.132 p = 0.115	R = 0.101 p = 0.235	R = 0.113 p = 0.175	R = -0.038 p = 0.654	R = -0.088 p = 0.298
Peak External Rotation Moment	R = -0.009 p = 0.914	R = -0.159 p = 0.068	R = -0.206 p = 0.019	R = 0.010 p = 0.903	R = -0.018 p = 0.826	R = -0.057 p = 0.501	R = 0.023 p = 0.784	R = -0.073 p = 0.385	R = -0.109 p = 0.198	R = -0.113 p = 0.176	R = -0.175 p = 0.035	R = -0.222 p = 0.008

[1] *Adjusted for baseline gait variables.*

[2] *Adjusted for baseline gait variables, age, sex, and BMI.*

Table 4. Associations between postoperative gait variables and preoperative passive range of motion (ROM). Shaded boxes highlight $p < 0.05$.

	Flexion Range of Motion (ROM)			Abduction ROM			Adduction ROM			External Rotation ROM			Internal Rotation ROM		
	Unadjusted	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]	*Unadjusted*	*Adjusted* [1]	*Adjusted* [2]
Sagittal Plane Hip Range of Motion	R = 0.212	R = 0.048	R = 0.023	R = -0.006	R = -0.112	R = -0.115	R = 0.125	R = -0.017	R = 0.048	R = 0.060	R = -0.084	R = -0.061	R = 0.030	R = -0.027	R = 0.008
	p = 0.014	p = 0.579	p = 0.796	p = 0.945	p = 0.197	p = 0.190	p = 0.150	p = 0.844	p = 0.584	p = 0.506	p = 0.347	p = 0.503	p = 0.737	p = 0.760	p = 0.930
Peak Flexion Moment	R = -0.055	R = -0.221	R = -0.215	R = 0.002	R = -0.090	R = 0.100	R = 0.056	R = 0.004	R = -0.009	R = -0.026	R = -0154.	R = -0.160	R = 0.005	R = 0.034	R = 0.042
	p = 0.524	p = 0.010	p = 0.014	p = 0.983	p = 0.301	p = 0.256	p = 0.520	p = 0.963	p = 0.916	p = 0.773	p = 0.085	p = 0.077	p = 0.955	p = 0.709	p = 0.647
Peak Extension Moment	R = 0.149	R = 0.099	R = 0.083	R = -0.072	R = -0.048	R = -0.066	R = -0.121	R = -0.093	R = -0.103	R = 0.219	R = 0.229	R = 0.217	R = -0.054	R = -0.048	R = -0.039
	p = 0.084	p = 0.253	p = 0.394	p = 0.403	p = 0.584	p = 0.453	p = 0.162	p = 0.284	p = 0.243	p = 0.013	p = 0.010	p = 0.016	p = 0.545	p = 0.598	p = 0.672
Peak Adduction Moment	R = 0.029	R = -0.011	R = -0.050	R = 0.018	R = 0.054	R = 0.044	R = -0.119	R = -0.101	R = -0.108	R = 0.013	R = -0.049	R = -0.041	R = -0.168	R = -0.144	R = -0.136
	p = 0.737	p = 0.902	p = 0.569	p = 0.737	p = 0.532	p = 0.614	p = 0.168	p = 0.244	p = 0.218	p = 0.884	p = 0.586	p = 0.656	p = 0.060	p = 0.110	p = 0.134
Peak Abduction Moment	R = 0.077	R = -0.034	R = -0.039	R = 0.055	R = 0.046	R = 0.056	R = 0.204	R = 0.161	R = 0.170	R = -0.062	R = -0.145	R = -0.118	R = 0.058	R = 0.094	R = 0.094
	p = 0.377	p = 0.696	p = 0.656	p = 0.528	p = 0.596	p = 0.524	p = 0.018	p = 0.063	p = 0.052	p = 0.485	p = 0.105	p = 0.194	p = 0.516	p = 0.297	p = 0.301
Peak Internal Rotation Moment	R = 0.174	R = 0.109	R = 0.075	R = 0.167	R = 0.058	R = 0.043	R = 0.093	R = -0.025	R = -0.035	R = 0.196	R = 0.161	R = 0.170	R = -0.140	R = -0.138	R = -0.126
	p = 0.043	p = 0.211	p = 0.396	p = 0.053	p = 0.505	p = 0.623	p = 0.282	p = 0.773	p = 0.691	p = 0.027	p = 0.072	p = 0.060	p = 0.119	p = 0.126	p = 0.168
Peak External Rotation Moment	R = -0.066	R = -0.138	R = -0.154	R = 0.052	R = 0.031	R = 0.020	R = 0.073	R = 0.092	R = 0.078	R = -0.135	R = -0.185	R = -0.183	R = 0.044	R = 0.047	R = 0.064
	p = 0.447	p = 0.112	p = 0.078	p = 0.552	p = 0.718	p = 0.817	p = 0.401	p = 0.289	p = 0.374	p = 0.130	p = 0.038	p = 0.043	p = 0.625	p = 0.600	p = 0.482

[1] *Adjusted for baseline gait variables.*

[2] *Adjusted for baseline gait variables, age, sex, and BMI.*

Table 5. Associations between postoperative gait variables and preoperative hip abductor strength. Shaded boxes highlight $p < 0.05$.

	Abductor Strength		
	Unadjusted	*Adjusted*[1]	*Adjusted*[2]
Sagittal Plane Hip Range of Motion	R = -0.110 p = 0.268	R = -0.240 p = 0.015	R = -0.100 p = 0.326
Peak Flexion Moment	R =- 0.045 p = 0.955	R = -0.085 p = 0.397	R = -0.146 p = 0.149
Peak Extension Moment	R = 0126. p = 0.206	R = 0.064 p = 0.522	R = 0.097 p = 0.341
Peak Adduction Moment	R = 0.266 p = 0.007	R = 0.211 p = 0.034	R = 0.266 p = 0.008
Peak Abduction Moment	R =- 0.135 p = 0.173	R = -0.201 p = 0.043	R = 0.216 p = 0.032
Peak Internal Rotation Moment	R = 0.080 p = 0.422	R = 0.003 p = 0.979	R = 0.012 p = 0.904
Peak External Rotation Moment	R = 0.304 p = 0.022	R = 0.204 p = 0.040	R = 0.197 p = 0.050

[1] *Adjusted for baseline gait variables.*

[2] *Adjusted for baseline gait variables, age, sex, and BMI.*

Table 6. Results of stepwise multiple regression analysis predicting postoperative gait variables.

	Adjusted R^2	**Predictor**	**Standardized Regression Coefficient**	**Regression Coefficient (95% Confidence Interval)**	**p value**
Sagittal Plane Dynamic Hip Range of Motion	0.292	Preoperative Sagittal Plane Dynamic Hip Range of Motion	0.567	0.563 (0.416, 0.709)	<0.001
N=143		HHS ADL Function	-0.067	-0.064 (-0.205, 0.077)3.8 (2.2, 5.3)	0.370
Peak Flexion Moment N=145	0.254	Preoperative Flexion Moment	0.509	0.660 (0.476, 0.844)	<0.001
Peak Extension Moment N=145	0.161	Preoperative Extension Moment	0.408	0.578 (0.365, 0.792)	<0.001
Peak Adduction Moment	0.154	Preoperative Peak Adduction Moment	0.373	0.334 (0.197, 0.471)	<0.001
N=143		HHS ADL Function	-0.179	-0.076 (-0.141, -0.011)	0.022
Peak Abduction Moment N=131	0.331	HHS	0.838	0.051 (0.010, 0.092)	0.016
		HHS Pain	-0.643	-0.063 (-0.109, -0.017)	0.007
		Preoperative Peak Abduction Moment	0.550	0.566 (0.412, 0.719)	<0.001
		HHS Gait Function	-0.407	-0.057 (-0.111, -0.004)	0.037
Peak Internal Rotation Moment N=145	0.383	Preoperative Peak Internal Rotation Moment	0.622	0.667 (0.529, 0.806)	<0.001
Peak External Rotation Moment N=116	0.312	Preoperative Peak External Rotation Moment	0.565	0.638 (0.463, 0.812)	<0.001
		HHS Pain	-0.131	-0.003 (-0.007, 0.001)	0.105
		Flexion Contracture	-0.103	-0.045 (-0.114, 0.024)	0.198

Figure Captions

Figure 1. Hip motion and external moments for a representative subject identified as having values for most gait variables near the group mean. In this study, we analyzed the dynamic range of motion (from peak flexion to peak extension) and peak moments in each plane. Note that the external adduction moment often has two relative maxima; the higher value of the two was selected for analysis.

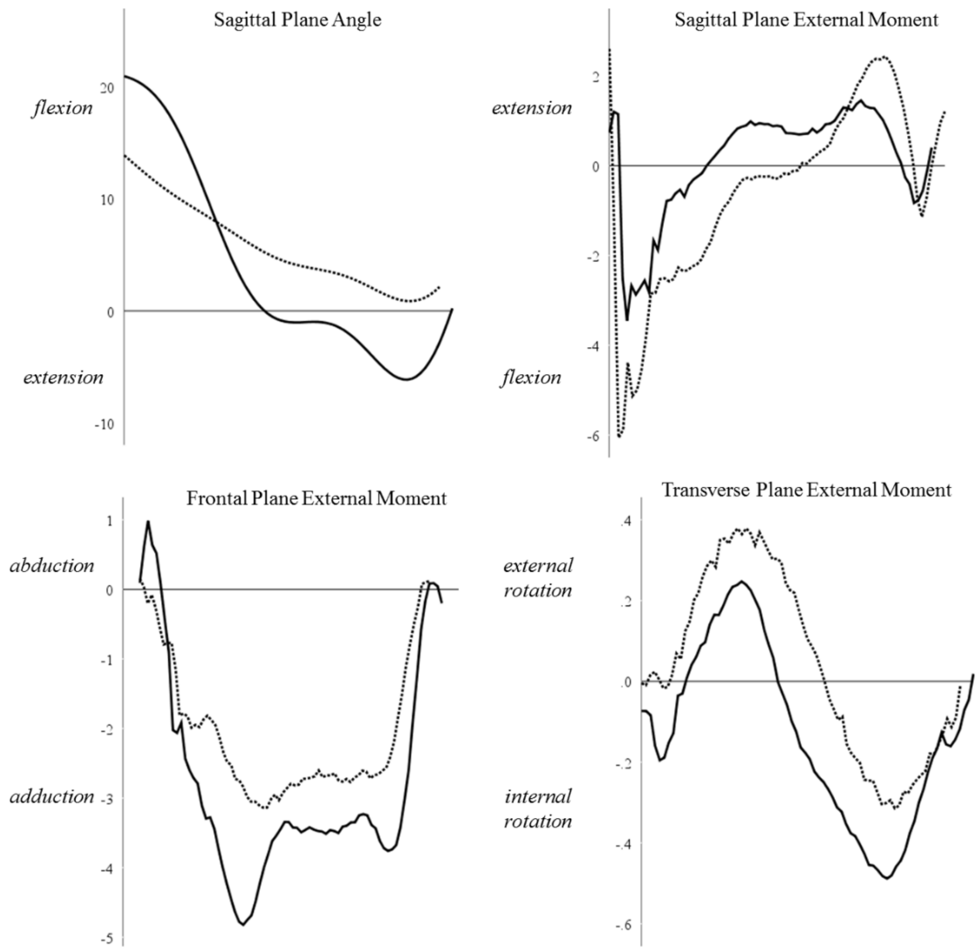

Figure 2. Flow diagram illustrating subject selection from the data repository.