Are Harris Hip Scores and Gait Mechanics Related Before and After THA?

Omar A. Behery MPH, Kharma C. Foucher MD, PhD

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Abstract

Background Discordance between subjective and objective functional measures hinders the development of new ways to improve THA outcomes.

Questions/purposes We asked if (1) any kinematic or kinetic gait variables are correlated with preoperative Harris hip scores (HHS), (2) any kinematic or kinetic gait variables are correlated with postoperative HHS, and (3) pre- to postoperative changes in any kinematic or kinetic gait variables are associated with the change in HHS?

Methods For this retrospective study, an institutional review board-approved data repository that included all

individuals who participated in motion analysis research studies was used to identify subjects evaluated before ($n = 161$) and at least 6 months after primary unilateral THA ($n = 156$). Selected kinematic (sagittal plane dynamic hip ROM and kinetic (peak external moments about the hip in the sagittal, frontal, and transverse planes) gait variables were collected at subjects' self-selected normal walking speeds. We used first-order partial correlations to identify relationships between HHS and gait variables, controlling for the influence of speed.

Results Preoperative HHS correlated with hip ROM ($R_{\text{lspeed}} = 0.260$; $p < 0.001$) and the peak extension moment ($R_{\text{lspeed}} = 0.164$; $p = 0.038$), postoperative HHS correlated with the peak internal rotation moment ($R_{\text{lspeed}} = 0.178$; $p = 0.034$), and change in HHS correlated with change in hip ROM ($R_{\text{lspeed}} = 0.288$; $p = 0.001$) and peak external rotation moment ($R_{\text{lspeed}} = 0.291$; $p = 0.002$). Similar associations were seen when the HHS pain and function were analyzed separately.

Conclusions This study identified relationships between a common clinical outcome measure and specific, modifiable gait adaptations that can persist after THA—ROM and transverse plane gait moments. Addressing these aspects of gait dysfunction through focused rehabilitation could be a new strategy for improving clinical outcomes. Prospective studies are needed to evaluate this concept.

Level of Evidence Level III, diagnostic study. See the Instructions for Authors for a complete description of levels of evidence.

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

This work was performed at Rush University Medical Center, Chicago, IL, USA.

O. A. Behery
Rush Medical College, Rush University Medical Center,
Chicago, IL, USA

K. C. Foucher (✉)
Department of Kinesiology and Nutrition, University of Illinois
at Chicago, 1919 W Taylor, 650 AHSB, Chicago, IL 60612,
USA
e-mail: kfouch1@uic.edu

Introduction

THA is one of the most successful orthopaedic interventions. Ten-year survivorship exceeds 90% for most implant

types [21, 33]. However, some measurable surgical end-points, even when they suggest success, do not always result in satisfied patients or high patient-centered outcomes scores [9, 22, 35, 41]. Another way to measure THA success is using benchmarks for improvement of clinical outcome scores. Examples include the Outcome Measures in Rheumatology and Osteoarthritis Research Society International consensus responder criteria [42], minimum important difference, or minimum clinically important difference. By these benchmarks, between 7% and 15% of patients having primary unilateral THAs do not experience a large enough change in clinical outcome scores to be perceived as important or meaningful to the patient [5, 24, 30–32, 39]. As patient-oriented definitions of success are becoming increasingly emphasized, more efforts to improve patient-oriented outcomes are needed. Functional outcomes are of particular concern because of the high priority patients place on returning to activities that are important to them [26, 27, 35].

A major obstacle to improving patient outcomes, whether through surgical innovation or new rehabilitation approaches, is that our conventional questionnaire-based outcome measures cannot tell us what specific interventions would improve outcomes. Quantitative gait analysis has been used to directly evaluate function during walking and other activities before and after THA [13, 40]. Commonly observed functional deficits include altered gait kinematics, specifically hip ROM in the sagittal and frontal planes, and altered gait kinetics, such as a reduced peak external hip adduction moment (which reflects abnormal hip abductor function). These gait measures provide specific information regarding muscle function during walking, a meaningful and relevant activity. Thus, understanding how these variables are related to clinical outcome scores could lead to better perioperative management approaches that could successfully improve outcomes.

The purpose of this retrospective cohort study was to determine how specific gait kinematics (hip motion) and kinetics (peak external moments about the affected hip) measured before and 1 year after primary unilateral THA were related to clinical outcome scores taken at the same time. We asked three questions: (1) Are any kinematic or kinetic gait variables correlated with preoperative Harris hip score (HHS)? (2) Are any kinematic or kinetic gait variables correlated with postoperative HHS? (3) Are pre- to postoperative changes in any kinematic or kinetic gait variables associated with the change in HHS?

Patients and Methods

We queried an institutional review board-approved data repository of participants of a motion analysis laboratory

Table 1. Characteristics of the study subjects (99 women, 89 men)

Characteristics	Mean (SD)	Median	Range
Age* (years)	60 (10)	62	26–85
BMI* (kg/m ²)	29.5 (5)	27	16–47
Preoperative Harris hip score	58 (14)	59	32–89
Postoperative Harris hip score	92 (10)	96	46–100
Change in Harris hip score	35 (16)	36	–10 to 65
Percent change in Harris hip score	71 (46)	61	–13 to 197
Followup time (months)	15 (4)	13	16 to 37

* At preoperative evaluation.

study to identify subjects for this retrospective cohort study. Available subjects underwent primary unilateral THA between 1994 and 2005 and had participated in biomechanical studies of preoperative and/or postoperative THA gait biomechanics. All gait analyses were conducted for research purposes involving patients who had primary unilateral THAs. There were no age restrictions, restrictions in functional ability, pain levels, or disease severity levels for any of the original studies. All of the original studies excluded patients with bilateral hip osteoarthritis, prior joint replacements, or pain or other symptoms in any lower extremity joint in addition to the affected hip. THAs were performed by seven surgeons from two practices. Two of the original studies specifically involved minimally invasive surgical approaches, but otherwise patient selection, surgical approach, and perioperative management were per the surgeon's usual care and were not dictated by the design of any of the original studies. For the original studies, subjects meeting exclusion criteria were enrolled sequentially from the surgeons' practices, therefore the subjects included in our study are likely representative of the patient population of a large high-volume urban medical center such as the one where the study was conducted. Results for some of the original studies in which these subjects were enrolled have been reported [15, 16, 19, 28]. For the current study, subjects were not considered if the only postoperative evaluation had occurred fewer than 6 months after surgery. One hundred eighty-eight subjects initially were identified (Table 1), and 124 to 161 were available to address each study question (Fig. 1). These numbers vary because the maximum number of subjects with available data were used to address each study question, without regard to the design of the subjects' original studies or whether each subject completed all activities required by the original study in which the subject was enrolled. For example, it is more likely that a subject who was included in the preoperative analyses but not the postoperative analyses in the current study, originally had been enrolled in a study that did not require a postoperative evaluation, rather than having been lost to followup.

Fig. 1 The diagram shows identification of study subjects from the database. HHS = Harris hip score.

A previously described gait analysis method and marker system were used for all subjects [2, 3, 28]. Briefly, the three-dimensional (3-D) position of reflective markers placed at bony landmarks of the lower extremities (iliac crest, greater trochanter, lateral knee line, lateral malleolus, calcaneus, and 5th metatarsal) was recorded by an optoelectronic camera system (Qualisys North America, Deerfield, IL, USA) as subjects walked across a 10-m walkway at self-selected normal speeds. The ground reaction force was measured by a multicomponent force plate (Bertec, Columbus, OH, USA) embedded in the walkway. Marker positions were used to calculate time-distance parameters and dynamic ROM in the sagittal plane (peak flexion-peak extension) for the hip, knee, and ankle for one full gait cycle. The 3-D positions of the markers, along with the location and magnitude of the ground reaction force measured from the force plate, allow calculation of external moments in the sagittal, frontal, and transverse planes using inverse dynamics. These external moments must be balanced by equal and opposite internal moments, which primarily are produced by the muscles. Therefore the external moments in each plane reflect net activity of a specific corresponding muscle group. The peak external moments that were of interest in our study were flexion, extension, adduction, abduction, internal rotation, and external rotation about the hip. These moments were normalized by each subject's body weight multiplied by height (%BW × HT) to avoid detecting differences between subjects attributable solely to size [37]. Gait variables for the surgically treated hip were averaged from each subject's normal speed trials (two to five per subject).

The HHS [23] was administered before each gait test. It is a widely used orthopaedic outcome measure that has been shown to be reliable and valid in assessment of the

clinical outcome of THA with psychometric properties comparable to other measures [43]. The HHS includes sections on pain, function, absence or presence of deformity, and passive ROM, and is scored from 0 (worst) to 100 (best). By convention, postoperative scores greater than 70 are considered fair, scores greater than 80 are considered good, and scores greater than 90 are considered excellent. No HHS-specific benchmarks for pre- to postoperative improvement have been reported; however, for an instrument that covers similar domains (the Hip disability and Osteoarthritis Outcome Score [38]), the threshold for minimal clinically important improvement was reported to be 35% to 55% [41].

To test for associations between HHS and gait variables, we used Pearson and Spearman's correlation coefficients, as appropriate, based on the distributions of the variables. (The postoperative HHS was skewed to the right.) Before statistically addressing our study questions, we tested for a potential confounding influence of walking speed on the gait variables [36, 4] and on the HHS [1, 18]. When necessary, we used first-order partial Pearson correlations to control for the effect of walking speed in addressing the study questions.

Results

Higher values of preoperative HHS were associated with higher values of the preoperative dynamic hip ROM, peak flexion moment, peak extension moment, peak abduction moment, and peak external rotation moment ($R = 0.231$ – 0.314 ; $p \leq 0.003$) but not the peak adduction or internal rotation moments ($p = 0.488$ and $p = 0.095$, respectively).

Fig. 2A–B The scatterplots show that patients with higher preoperative HHS also had (A) higher dynamic sagittal plane hip ROM and (B) peak extension moment. The dashed vertical lines indicate HHS scores that, by convention, are considered fair, good, and excellent after surgery. Unadjusted correlation coefficients are shown. These relationships persisted when adjusting for the influence of walking speed on both variables.

Walking speed was correlated with the HHS ($R = 0.323$; $p < 0.001$) and all gait variables ($R = 0.178$ – 0.614 ; $p < 0.001$ to $p = 0.018$). After controlling for speed (Table 2), the associations persisted between the preoperative HHS and the dynamic sagittal plane hip ROM and peak extension moment. Better HHS were associated with higher values for both of these gait variables (Fig. 2).

Higher postoperative HHS were associated with higher postoperative peak adduction, internal rotation, and external rotation moments (Spearman's $\rho = 0.183$ – 0.264 , $p = 0.029$ – 0.001 ; other relationships $p \geq 0.124$). However, faster walking speeds were associated with higher postoperative HHS (Spearman's $\rho = 0.369$; $p < 0.001$) and with all gait variables (Spearman's $\rho = 0.161$ – 0.604 ; $p < 0.001$ – 0.044). After controlling for speed (Table 2), the only association remaining was between the postoperative HHS and the peak internal rotation moment (Fig. 3).

Subjects who experienced greater change in HHS also had larger increases in hip ROM ($R = 0.300$; $p = 0.001$) and peak external rotation moment ($R = 0.354$; $p < 0.001$; otherwise $p \leq 0.179$).

However, having a greater postoperative improvement change in walking speed also was associated with more improvement in HHS ($R = 0.243$; $p = 0.006$) and in all gait variables ($p \leq 0.007$) except hip ROM ($p = 0.308$). Nevertheless, the associations between change in HHS and change in gait variables persisted when controlling for speed (Table 2). Specifically, patients with more clinical improvement also had more improvement in ROM and peak external rotation moment (Fig. 4).

Next, we repeated these analyses using the HHS pain and function scales separately to determine whether either subscore was related to gait analysis measures. There were no observed relationships between pain and walking speed before or after surgery or between change in pain and change in walking speed ($R = 0.120$; $p = 0.154$) and there were few associations between pain and kinematic or kinetic gait variables. Before surgery, having more pain was associated with lower peak extension moments (Spearman's $\rho = 0.157$; $p = 0.038$). A greater decrease in pain was associated with greater increases in ROM (Spearman's $\rho = 0.267$; $p = 0.001$) and increases in the peak external rotation moment (Spearman's $\rho = 0.179$, $p = 0.032$; otherwise $p = 0.068$ – 0.452). Because of the positive association between walking speed and gait variables, we still examined the first order partial correlations between HHS pain scores and gait (Table 3). This analysis confirmed that having a greater change in pain score was associated with greater increases in ROM and the peak external rotation moment after adjusting for speed. Higher function scores were associated with higher walking speeds before ($R = 0.468$; $p < 0.001$) and after surgery ($Rho = 0.366$; $p < 0.001$), and change in walking speed was associated with change in function scores ($R = 0.399$; $p < 0.001$). After controlling for walking speed, the same relationships seen between gait variables total HHS were seen with HHS function (Table 4). In addition, postoperative HHS function and the hip adduction moment were correlated.

Finally, we used stepwise linear regression analysis to more specifically quantify the association of gait variables with HHS. The dependent variable was the change in HHS. We included age, sex, and BMI as predictor variables, along with change in walking speed and change in each kinematic and kinetic gait variables. The criterion for variable entry was a p value of 0.05 or less on the partial F test, and the criterion for subsequent removal was a p value of 0.1 or greater. The resulting model included two predictors—change in peak external rotation moment and change in hip ROM. The adjusted R^2 was 0.196 indicating

Table 2. First-order partial Pearson correlation coefficients (95% CI) for Harris hip scores versus gait variables

Gait variable	Before THA	After THA	Preoperative to postoperative change
Dynamic hip ROM	$R_{\text{lspeed}} = 0.260$ (0.100 to 0.403) $p < 0.001$	$R_{\text{lspeed}} = 0.033$ (−0.132 to 0.239) $p = 0.693$	$R_{\text{lspeed}} = 0.288$ (0.143 to 0.437) $p = 0.001$
Peak flexion moment	$R_{\text{lspeed}} = 0.070$ (−0.075 to 0.226) $p = 0.379$	$R_{\text{lspeed}} = -0.084$ (−0.252 to 0.042) $p = 0.323$	$R_{\text{lspeed}} = -0.039$ (−0.184 to 0.127) $p = 0.669$
Peak extension moment	$R_{\text{lspeed}} = 0.164$ (0.002 to 0.301) $p = 0.038$	$R_{\text{lspeed}} = -0.092$ (−0.261 to 0.053) $p = 0.277$	$R_{\text{lspeed}} = -0.051$ (−0.209 to 0.118) $p = 0.573$
Peak adduction moment	$R_{\text{lspeed}} = -0.030$ (−0.202 to 0.148) $p = 0.708$	$R_{\text{lspeed}} = 0.151$ (−0.061 to 0.274) $p = 0.072$	$R_{\text{lspeed}} = 0.106$ (−0.123 to 0.315) $p = 0.244$
Peak abduction moment	$R_{\text{lspeed}} = 0.098$ (−0.041 to 0.235) $p = 0.218$	$R_{\text{lspeed}} = -0.004$ (−0.180 to 0.173) $p = 0.996$	$R_{\text{lspeed}} = 0.034$ (−0.112 to 0.172) $p = 0.711$
Peak internal rotation Moment	$R_{\text{lspeed}} = 0.039$ (−0.108 to 0.195) $p = 0.628$	$R_{\text{lspeed}} = 0.178$ (0.059 to 0.346) $p = 0.034$	$R_{\text{lspeed}} = 0.089$ (−0.090 to 0.265) $p = 0.330$
Peak external rotation moment	$R_{\text{lspeed}} = 0.106$ (−0.033 to 0.237) $p = 0.181$	$R_{\text{lspeed}} = 0.134$ (−0.063 to 0.275) $p = 0.113$	$R_{\text{lspeed}} = 0.291$ (0.141 to 0.430) $p = 0.001$

that nearly 20% of the variation in clinical improvement could be predicted by improvement in these two gait variables. The regression coefficient for change in external rotation moment was 27.8 (95% CI, 14.9–40.6) which indicated that for each % body weight $\times$ height increase in this gait variable postoperatively, a 27.8 point increase in HHS could be expected. The coefficient for change in hip ROM was 0.821 (95% CI, 0.37–1.3) which indicated that an increase of 10 points in HHS could be expected for approximately every 8° improvement in dynamic sagittal plane hip motion during walking. In addition, the standardized coordinates for the change in external rotation moment and hip ROM were, respectively, 0.345 and 0.289, which indicates that the contributions of each gait variable were approximately equal in the model.

Discussion

As many as 1/2 of patients having THAs have some persistent functional limitations [30]. Numerous physical therapy interventions have been attempted [10, 11, 36], but discordance between subjective and objective functional measures hinders the development of new ways to improve THA outcomes. The rationale for this study was that a more specific understanding of the relationships between

functional impairment and clinical scores could lead to new interventions to improve outcomes. We asked whether gait kinematics and kinetics are associated with HHS before or after THA and whether change in gait variables was associated with change in HHS. By accounting for the effects of walking speed in this analysis, we conclude that the HHS successfully reflects some specific aspects of gait function and, conversely, that gait kinematics and kinetics successfully reflect clinical status. Furthermore, we showed that pain and pain improvement, as assessed through the HHS, is not the primary driver of these relationships. In other words, the association between greater clinical improvement and larger motions or external moments goes beyond patients simply having less pain and consequently walking faster after THA. The most consistent finding was that improved ROM and transverse plane hip moments were associated with improved HHS scores.

As with any secondary analysis, some important limitations arose because of potential variation in the study design of the original studies. For example, some studies involved preoperative or postoperative evaluations but not both; from the documentation available, it was not clear whether a subject who had missing data actually completed his or her study activities, withdrew, or was lost to followup. The most common reason for apparent loss to followup was that some studies did not require a

Fig. 3 The scatterplot shows that higher postoperative HHS were associated with higher peak internal rotation moments, but ceiling effects are evident. The dashed vertical lines indicate HHS scores that, by convention, are considered fair, good, and excellent after surgery. The R value shown refers to Spearman's rho. This relationship persisted when adjusting for the influence of walking speed on both variables.

Fig. 4A–B The scatterplots show that subjects with more improvement in HHS also had more improvement in the (A) dynamic sagittal plane hip ROM and the (B) peak external rotation moment. Unadjusted correlation coefficients are shown. These relationships persisted when adjusting for the influence of walking speed on both variables.

postoperative evaluation in the time that we required for the current analysis. We decided to use the maximum amount of data possible to answer each study question. We verified that there were no preoperative gait or HHS differences ($p = 0.142$ – 0.986) between subjects for whom two visits were available ($n = 124$) and those missing postoperative data. A second limitation of this study is that the HHS has known ceiling effects [49]. Twenty-five percent of patients in this cohort had the maximum score of 100 after THA. It is not possible to know whether the instrument is limited in its ability to completely capture the full range of clinical improvement that is possible with contemporary surgery or whether all of these perfect scores truly represent an optimal outcome. The HHS was designed for use only as a total score; unlike the Hip disability and Osteoarthritis Outcome Score or WOMAC instruments, the pain and function sections have not been validated for use as independent subscales. For this reason, we based our study questions on the HHS total score and analyzed the subsections only to provide additional context. Finally, the gait analysis method has some inherent limitations; most notably soft tissue artifact can adversely affect marker tracking. This may be of particular concern in subjects with high BMIs. In addition, only sagittal plane kinematics were available owing to the marker set and processing methods used.

Before surgery, several specific gait variables were associated with clinical status as reflected by the HHS. As in previous studies using the HHS and other outcome measures [7, 18, 34, 48], faster walking speeds were associated with better HHS. Even after controlling for the influence of speed, however, we found that higher HHS before surgery were associated with greater hip ROM and higher peak extension moments (which reflects net activity of hip flexors during the second $\frac{1}{2}$ of stance). Sagittal plane gait anomalies were reported in several studies of patients with hip osteoarthritis [12, 17, 29, 50]. One of these studies also showed that the peak extension moment decreased as HHS pain scores decreased (indicating worse pain) in 19 subjects with end-stage hip osteoarthritis [29]. Our results agree with that finding; having higher (better) HHS total score and pain and function subscores were associated with higher peak extension moments before surgery. Our study also linked hip ROM during walking with HHS scores. However, even subjects with very high HHS values had substantial gait impairment by these two measures. The 10 subjects who had preoperative HHS greater than 80, which would be considered a good postoperative score, had mean (SD) ROM of 19° (5°) and mean (SD) peak extension moment of $1.63\% \text{ BW} \times \text{HT}$ ($0.77\% \text{ BW} \times \text{HT}$). In a previous study [17] in which gait variables of subjects with hip osteoarthritis were compared with those for asymptomatic control subjects, hip ROM for

Table 3. First-order partial Pearson correlation coefficients (95% CI) for Harris hip pain scores versus gait variables

Gait variable	Before THA	After THA	Preoperative to postoperative change
Dynamic hip ROM	$R_{\text{lspeed}} = 0.126$ (−0.024 to 0.280) $p = 0.113$	$R_{\text{lspeed}} = 0.062$ (−0.278 to 0.136) $p = 0.493$	$R_{\text{lspeed}} = 0.182$ (0.032 to 0.361) $p = 0.044$
Peak flexion moment	$R_{\text{lspeed}} = 0.068$ (−0.079 to 0.226) $p = 0.392$	$R_{\text{lspeed}} = -0.044$ (−0.195 to 0.070) $p = 0.625$	$R_{\text{lspeed}} = 0.045$ (−0.092 to 0.212) $p = 0.623$
Peak extension moment	$R_{\text{lspeed}} = 0.068$ (−0.095 to 0.216) $p = 0.396$	$R_{\text{lspeed}} = -0.087$ (−0.229 to 0.046) $p = 0.338$	$R_{\text{lspeed}} = -0.074$ (−0.229 to 0.082) $p = 0.413$
Peak adduction moment	$R_{\text{lspeed}} = -0.072$ (−0.230 to 0.094) $p = 0.362$	$R_{\text{lspeed}} = 0.058$ (−0.111 to 0.223) $p = 0.522$	$R_{\text{lspeed}} = 0.032$ (−0.169 to 0.226) $p = 0.294$
Peak abduction moment	$R_{\text{lspeed}} = 0.082$ (−0.065 to 0.233) $p = 0.300$	$R_{\text{lspeed}} = 0.004$ (−0.156 to 0.156) $p = 0.966$	$R_{\text{lspeed}} = 0.095$ (−0.052 to 0.238) $p = 0.294$
Peak internal rotation moment	$R_{\text{lspeed}} = -0.055$ (−0.221 to 0.114) $p = 0.060$	$R_{\text{lspeed}} = 0.141$ (−0.008 to 0.227) $p = 0.119$	$R_{\text{lspeed}} = 0.065$ (−0.101 to 0.229) $p = 0.476$
Peak external rotation moment	$R_{\text{lspeed}} = 0.092$ (−0.033 to 0.220) $p = 0.246$	$R_{\text{lspeed}} = 0.121$ (−0.047 to 0.267) $p = 0.184$	$R_{\text{lspeed}} = 0.256$ (0.117 to 0.390) $p = 0.004$

Table 4. First-order partial Pearson correlation coefficients (95% CI) for Harris hip function scores versus gait variables

Gait variable	Before THA	After THA	Preoperative to postoperative change
Dynamic hip ROM	$R_{\text{lspeed}} = 0.288$ (0.146 to 0.424) $p < 0.001$	$R_{\text{lspeed}} = 0.152$ (−0.016 to 0.331) $p = 0.093$	$R_{\text{lspeed}} = 0.340$ (0.200 to 0.482) $p < 0.001$
Peak flexion moment	$R_{\text{lspeed}} = 0.036$ (−0.099 to 0.162) $p = 0.649$	$R_{\text{lspeed}} = -0.121$ (−0.301 to 0.047) $p = 0.182$	$R_{\text{lspeed}} = -0.111$ (−0.260 to 0.055) $p = 0.221$
Peak extension moment	$R_{\text{lspeed}} = 0.267$ (0.127 to 0.392) $p = 0.001$	$R_{\text{lspeed}} = -0.086$ (−0.258 to 0.096) $p = 0.271$	$R_{\text{lspeed}} = -0.039$ (−0.226 to 0.151) $p = 0.672$
Peak adduction moment	$R_{\text{lspeed}} = 0.060$ (−0.135 to 0.249) $p = 0.452$	$R_{\text{lspeed}} = 0.159$ (−0.025 to 0.328) $p = 0.047$	$R_{\text{lspeed}} = 0.193$ (−0.040 to 0.398) $p = 0.033$
Peak abduction moment	$R_{\text{lspeed}} = 0.077$ (−0.067 to 0.224) $p = 0.331$	$R_{\text{lspeed}} = -0.027$ (−0.212 to 0.156) $p = 0.764$	$R_{\text{lspeed}} = -0.016$ (−0.184 to 0.164) $p = 0.859$
Peak internal rotation moment	$R_{\text{lspeed}} = 0.149$ (0.011 to 0.283) $p = 0.060$	$R_{\text{lspeed}} = 0.222$ (0.072 to 0.353) $p = 0.014$	$R_{\text{lspeed}} = 0.079$ (−0.097 to 0.250) $p = 0.384$
Peak external rotation moment	$R_{\text{lspeed}} = 0.084$ (−0.058 to 0.212) $p = 0.289$	$R_{\text{lspeed}} = 0.100$ (−0.093 to 0.260) $p = 0.271$	$R_{\text{lspeed}} = 0.275$ (0.105 to 0.427) $p = 0.002$

the control group was $32^{\circ}(6^{\circ})$, and the peak extension moment was $3.55\% \text{ BW} \times \text{HT}$ ($1.55\% \text{ BW} \times \text{HT}$) [17]. Therefore, although HHS values reflect these aspects of gait function, it is possible to have a high score and still have considerable gait impairment.

Our postoperative findings confirm and extend those of previous studies that showed walking speed is related to clinical outcome measures [7, 18, 34]. In addition, the peak internal rotation moment, which reflects net activity of muscles that laterally rotate the hip during late stance [14, 20], was correlated with the postoperative HHS after controlling for speed. Unfortunately, interpretation of this finding is complicated by the HHS ceiling effects, discussed previously. In subjects with the maximum HHS postoperatively, the peak internal rotation moment ranged from 0.11% to 0.96% $\text{BW} \times \text{HT}$. Previously described asymptomatic control subjects [17] had an internal rotation moment of 0.86% $\text{BW} \times \text{HT}$ (0.28% $\text{BW} \times \text{HT}$). This suggests that a perfect score can conceal functional limitations in the transverse plane. However, it also could indicate that dynamic transverse plane gait abnormalities are not necessarily clinically important. More work is needed to fully understand the implications of these findings. In either case, these findings show that the ability of the HHS to capture a specific aspect of postoperative function is limited.

Improvement in HHS was independently associated with hip external rotation moments. The peak external rotation moment is balanced by muscles that internally rotate the hip during the first $\frac{1}{2}$ of stance, when the hip is flexed. Among the muscles that are active during this portion of stance, the gluteus medius and minimus are the primary muscles that are positioned to control this activity [20]. Improving abductor strength is emphasized in many postoperative physical therapy regimens [8, 25]; however, there is insufficient evidence that these programs also improve clinical outcome scores [36]. Although causation cannot be inferred from these correlations, the link between improvement in HHS and the peak external rotation moment suggests that improving the subtle transverse plane role of the hip abductors may be important for clinical recovery. Future prospective studies are needed to determine how these relationships could be used to refine rehabilitation practices.

We showed that clinical outcomes as assessed using the HHS overlap in specific ways with the construct of function as assessed using quantitative gait analysis. This is important because questionnaires are limited in their ability to distinguish between pain and function [44, 47, 48] to characterize the specific aspects of muscle group dysfunction that correspond to functional limitations [34, 45, 46]. Finally, it is important to be mindful that higher HHS can mask important gait impairments, since pain is

weighted more highly than gait function in the HHS. Patients who have good or excellent clinical outcomes still may have functional deficits that are troublesome or limiting. There is precedent for using gait analysis and other performance-based functional testing to identify and improve function in patients who had THAs with poor clinical outcomes despite conventional rehabilitation [6]. Our study shows the potential for a broader role for gait analysis to identify subtle but clinically important deficits that could be targeted through rehabilitation.

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