Identifying Clinically Meaningful Benchmarks for Gait Improvement After Total Hip Arthroplasty

Kharma C. Foucher

Department of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, Illinois

Received 22 April 2015; accepted 23 July 2015
Published online 6 August 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/jor.22996

ABSTRACT: There are no established benchmarks for gait mechanics after total hip arthroplasty (THA). This study sought to identify minimum clinically important postoperative (MCIP) or minimum clinically important improvement (MCII) values for self-selected walking speed, sagittal plane dynamic hip range of motion (HROM) (peak flexion-peak extension) and peak hip adduction moments measured during quantitative gait analysis. Preoperative and 1-year postoperative data collected during quantitative gait analysis, along with Harris Hip Scores (HHS), for 145 subjects were collected from a motion analysis data repository. The MCIP (or MCII) was defined as the 75th percentile mark on a plot of the cumulative percent of subjects with HHS $\geq$ 80 versus the postoperative value (or change) in the respective variable. 95% confidence intervals (CI) were calculated. Logistic regression was used to test the association of age, sex, BMI, and preoperative HHS with benchmarks. The MCIP of speed was 1.34 m/s (95%CI 1.30, 1.37); MCII was 0.32 (0.30, 0.35) m/s. The HROM MCIP was 30.0° (29.4°, 30.7°); MCII was 13.3° (12.1°, 14.8°). The adduction moment MCIP was 4.2% Body Weight $\times$ Height (4.0, 4.4); MCII was 0.87 (0.57, 1.17) % Body Weight $\times$ Height. Women were more likely to achieve MCII for HROM and MCIP for adduction moment (ORs 2.4–11.6, $p \leq 0.031$). Lower BMI predicted HROM and adduction moment MCIPs (ORs 0.85–0.88, $p \leq 0.015$). Lower preoperative HHS predicted speed, HROM and adduction moment MCIIs (ORs 0.95–0.97, $p \leq 0.012$). With further validation, clinically-relevant gait benchmarks can enhance efforts to improve THA outcomes. © 2015 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 34:88–96, 2016.

Keywords: total hip arthroplasty; gait; outcomes assessment; rehabilitation; benchmarks

Over 300,000 people undergo total hip arthroplasty (THA) each year in the US alone; demand is rising, especially in middle aged patients.[1,2] Functional recovery is an important priority, as well as a key expectation, for patients undergoing THA.[3–5] Unfortunately, between 14 and 22% of patients report limitations in walking function and other physical activities, or do not have clinically meaningful functional improvement.[6–8] Abnormal gait mechanics may be a barrier to full restoration of physical function.[9–17] In recent reviews,[18,19] the most consistently reported spatiotemporal, kinematic, and kinetic gait deficits, are, respectively, reduced walking speed, reduced dynamic hip range of motion in the sagittal plane and reduced dynamic abductor function compared to control subjects. These aspects of gait are directly associated with self-reported gait function in THA patients.[20] Therefore, the longstanding calls in the literature for new ways to improve gait function are certainly justified, and moreover, improving gait mechanics may be one pathway to improving overall clinical and functional outcomes.

A barrier in the goal of improving gait mechanics after THA is that we do not yet have a definition of what constitutes an "acceptable" or "good" gait outcome. A tacit assumption is that normal walking mechanics is the goal, but this goal may be unattainable for many patients because of the significant impairment present before surgery.[9,11,17,21] Normal walking mechanics may also not necessarily be desirable, because high values of certain gait parameters may increase potentially damaging joint forces.[22–24] Finally, although we know from our recent work that there is an association between gait improvement and clinical improvement,[20] we do not yet know how much improvement, or what final postoperative outcome may be meaningful to a given patient. There is a need for clinically relevant benchmarks for gait improvement after THA.

Typically, gait variables before and after THA or versus a control group are compared and p values are reported to as an indication of statistical significance. Statistical significance does not, however, indicate a clinically meaningful finding. The idea of minimum clinically important improvement (MCII) is one of the strategies that has proposed to complement conventional statistical comparisons.[25] The concept of MCII was used here because it was attractive to anchor quantitative gait measures to a clinical instrument that evaluates function in a different way and incorporates other domains. In this study, the MCII concept was expanded to include a calculation of minimum clinically important postoperative (MCIP) values for gait measures, because preoperative gait evaluations are not always available in the literature.

Having benchmarks for a meaningful response could, for example, reveal that statistically significant gait differences between groups of subjects undergoing different rehabilitation techniques or different surgical approaches, are not actually likely to have clinical importance. Conversely, subtle differences identified between groups may not be statistically significant, but may make the difference between an individual patient having a clinically important change or not.

This study was performed at the Rush University Medical Center, Joan and Paul Rubschlager Motion Analysis Laboratory.
Grant sponsor: Rush Research Mentoring Program Young Investigator Research Fund.
Correspondence to: Kharma C. Foucher (T: 312-355-3948, F: 312-413-0319; E-mail: kfouch1@uic.edu)

The purpose of this study was to present a method for establishing attainable, clinically relevant benchmarks for MCII and MCIP values for selected gait variables. Because age, sex, BMI, and preoperative clinical status have been associated with functional recovery in some studies,[26–28] the secondary goal of this study was to preliminarily identify preoperative patient factors that may be associated with attaining gait benchmarks.

METHODS

Subjects

Subjects were identified from an IRB-approved data repository for this retrospective cohort study (Level of Evidence 3). Characteristics of this cohort have been previously presented.[20] Briefly, inclusion criteria were previous participation in IRB-approved studies of gait in subjects undergoing primary unilateral THA, and having both pre- and postoperative gait data included in the repository. Relevant inclusion and exclusion criteria for the original studies in which these subjects were enrolled included candidacy for primary unilateral THA, no other planned or anticipated joint surgeries, and no symptoms in any other lower extremity joint at the time of enrollment. All original studies excluded patients with a diagnosis of inflammatory arthritis. For the present analysis, the target follow-up time point was 1 year. Because of our previous work showing that gait kinematics and kinetics stabilize by 6 months after surgery,[29] subjects whose postoperative data were collected before this time point were not included. When more than one postoperative visit had been conducted, the visit closest to 1 year after surgery was selected. 145 subjects were identified who fit the specified inclusion criteria (61 ± 10 yrs, BMI $28.5 \pm 5.0\,kg/m^2$, 68 female). The indication for THA was listed as osteoarthritis for 123 subjects, avascular necrosis for 4 subjects, ankylosing spondylitis for 1 subject; diagnoses were not available for the remaining 17.

Motion Analysis

All subjects underwent gait analysis using standard methods described in detail elsewhere.[30,31] In addition, some pre- and postoperative gait data for the original studies in which these subjects participated,[29,32] as well as for this subject cohort,[17,20] have been previously reported. In brief, a multicomponent forceplate (Bertec, Columbus OH) measured ground reaction forces as subjects walked across a 10 m walkway at a range of self-selected speeds. Reflective markers were placed on the iliac crest, greater trochanter, lateral knee joint line, lateral malleolus, head of the second metatarsal, and lateral posterior aspect of the calcaneus. An optoelectronic camera system (Qualisys North America, Deerfield IL) tracked the motion of the markers. Joint centers were identified based on 3D marker positions and anthropometric measurements. Specifically, calipers were used to measure the distance between the medial and lateral knee and ankle joint lines. This measurement was bisected to determine the knee and ankle joint centers. The hip center was placed 2.5 cm distal to a point bisecting the ASIS and the pubic tubercle, which were located by palpation. Therefore the 3D joint center positions were determine by translating the 3D position of the respective marker by the distance calculated. Custom software (CFTC—Computerized Functional Testing Corporation, Chicago, IL) was used to determine spatiotemporal gait variables and, sagittal plane joint kinematics, from marker positions, and external moments in the sagittal, frontal, and transverse planes, using inverse dynamics. Note that the requirements for inverse dynamics calculations include knowledge of the 3D position of the proximal and distal ends and joint centers, and the inertial properties of each segment. Additional markers would have been needed to calculate frontal and transverse plane kinematics, but all needed information was present to compute 3D external moments. Moments were normalized to subject body weight and height (% BWH) to reduce the effect of body size overall, as well as the gender differences that are solely attributable to size.[33] Typically three trials were collected for the affected hip at a self-selected normal speed. Speed, sagittal plane dynamic hip range of motion (HROM), and peak external moments in each plane were averaged from these trials, at each visit. The variables of interest in this study were the speed, HROM and the peak external hip adduction moment because in meta-analyses these variables have been consistently identified as reduced compared to control subjects across studies.[18]

Clinical Outcome Measure

Because it was the instrument most commonly and most consistently used in the lab, the Harris Hip Score (HHS) was used here to characterize clinical status before and after THA. The same study personnel who performed the gait analysis test administered the HHS. The HHS is valid and reliable in determining clinical outcomes of THA.[34] It consists of 4 domains: pain, function (gait and activities of daily living), absence of deformity (e.g., leg length discrepancy, flexion contracture), and passive range of motion assessed by the examiner. The maximum score is 100. In the scoring, pain (worth 44 points) and function (worth 47 points) are most heavily weighted. For these subjects, the preoperative HHS was 56.5 ± 14 and the postoperative HHS 91.7 ± 10.5. By convention, a score above 80 is considered “good”.[34] This cutoff value was used for the subsequent anchoring procedure.

Statistical Analysis

Analyses were conducted using SPSS V.22 (IBM SPSS Statistics, Chicago, IL). To identify the MCII and MCIP for the gait variables, a method to identify clinically meaningful cutoffs for improvement in patient reported outcome measures described by Tubach and colleagues,[25] and adopted by others,[35,36] was used here. In the present study, the anchor was a “good” outcome via the HHS. The cumulative percent of subjects who had an HHS ≥ 80 was plotted against the change in each gait variable. Next, a logistic function was fitted to each curve, and the 75th percentile was calculated and determined to be the MCII. The MCII with 95%CI were determined for each gait variable. The proportion of subjects attaining an MCII for each variable was computed. This analysis was repeated for the 1-year postoperative value of each variable to determine the MCIP (example for the peak hip adduction moment shown in Fig. 1). Finally, logistic regression was used to determine whether the selected patient factors, age, sex (coded as female = 1, male = 0), BMI, and preoperative HHS were associated with having an MCII or MCIP for the selected gait variables. Odds ratios with 95% confidence intervals were determined.

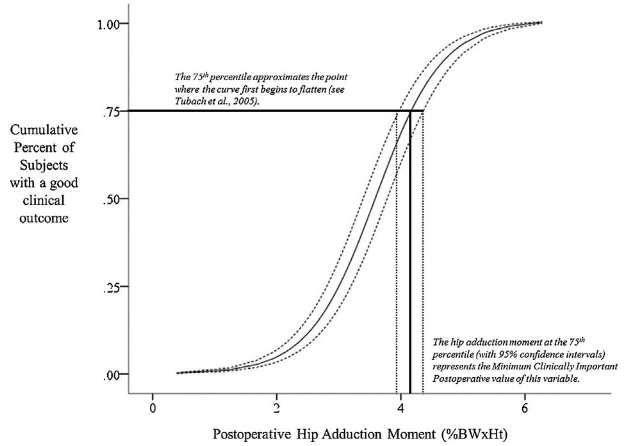

Figure 1. Example of determining the minimum clinically important postoperative peak hip adduction moment by identifying the value of that gait variable at which 75% of subjects had a good clinical outcome.

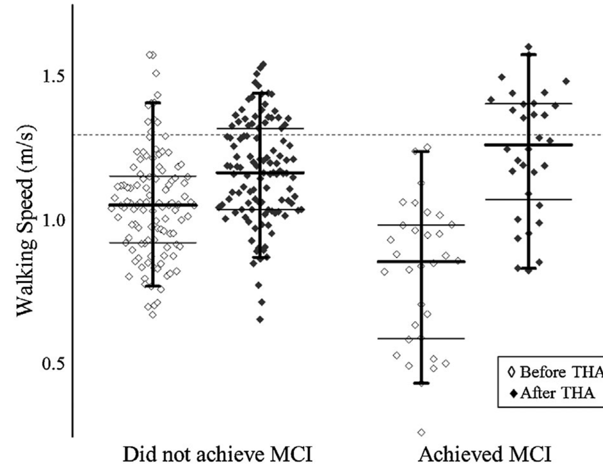

Figure 3. Box and dot plots illustrating the preoperative and postoperative values of self-selected normal walking speed for subjects who attained an MCII for this variable and those who did not. In this figure, and in figures 5 and 7, horizontal lines represent the median, 25th and 75th percentile; whiskers represent the 5th and 95th percentile. The dotted line across the entire graph represents the mean value for a previously described [29] group of healthy subjects.

RESULTS

Walking Speed

After THA, self-selected normal walking speed improved by 0.18 ± 0.19 m/s from a preoperative speed of 1.0 ± 0.2 m/s to a postoperative speed of 1.2 ± 0.12 m/s ($p < 0.001$). The MCIP (Fig. 2A) for speed was 1.34 m/s (1.30, 1.37) and the MCII (Fig. 2B) for speed was 0.32 m/s (0.30, 0.35). 37.4% and 21.6% of subjects, respectively, achieved the MCIP and MCII for walking speed. Preoperative walking speed was higher for those who did not achieve the MCII compared to those who did (respectively, 1.06 ± 0.19 vs 0.81 ± 0.25 m/s, $p = 0.001$), but postoperative speeds were not significantly different ($p = 0.076$; Fig. 3). Younger age was statistically associated with achieving the MCIP (Table 1), however this association was not strong. Higher BMI, lower preoperative HHS, and lower preoperative speeds were associated with attaining the MCII (Table 1).

Sagittal Plane Dynamic Hip Range of Motion

HROM improved by $9.3° \pm 5.7°$ (range $-9.7°$ to 23°), from $16.3° \pm 6.0°$ to $25.7° \pm 5.9°$. Based on paired t-tests, this change was statistically significant ($p < 0.001$). The MCIP for HROM was 30.0° (29.4°, 30.7°) and, despite this statistically significant improvement, only 19.3% (13.1%, 26.2%) of subjects achieved this HROM after surgery (Fig. 4A). The MCII for HROM was 13.3° (12.1°, 14.8°). 16.6% (11.0%, 22.8%) subjects attained this MCII (Fig. 4B). While preoperative HROM was higher for the subjects who failed to attain the MCII (Fig. 5), postoperative HROM was lower (24.8 ± 5.8 vs. 29.4 ± 4.5, $p = 0.001$). Women and people with a lower BMI were more likely to have an MCIP for HROM

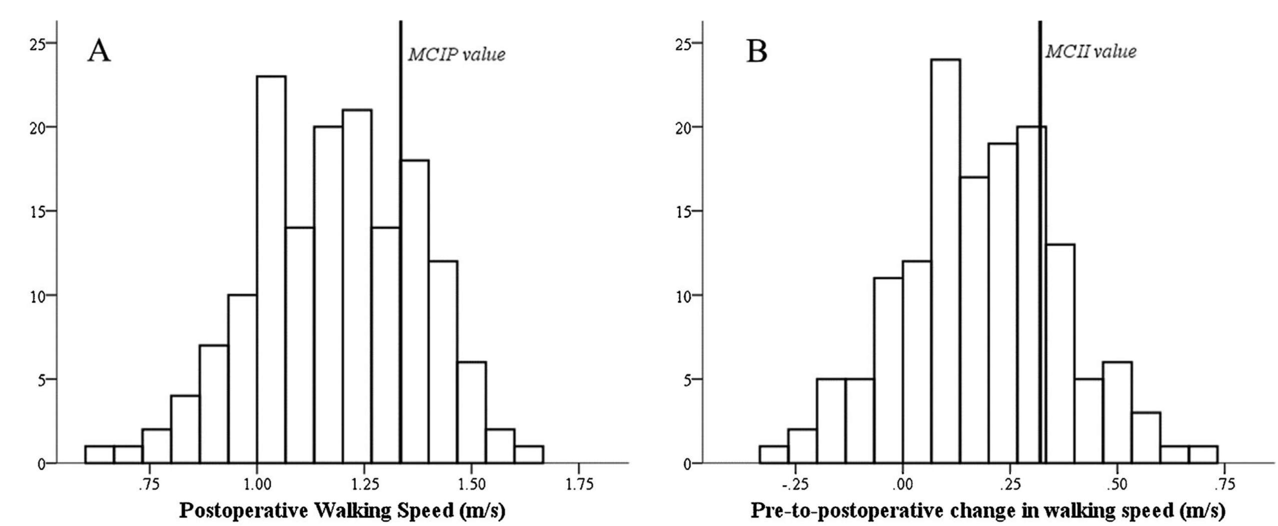

Figure 2. (A) Histogram of postoperative walking speed. Vertical line indicates the minimum clinically important postoperative (MCIP) value. (B) Histogram of the preoperative-to-postoperative change in walking speed. Vertical line indicates the minimum clinically important improvement (MCII) for walking speed.

Table 1. Associations Between Selected Preoperative Patient Factors and Attaining a Minimal Clinically Important Postoperative (MCIIP) Value or Minimal Clinically Important Improvement (MCII) for Speed, Hip Range of Motion, and Peak Hip Adduction Moment

	Speed		Sagittal Plane Hip Range of Motion		Peak Hip Adduction Moment	
	MCIP	MCII	MCIP	MCII	MCIP	MCII
Age	β = −0.040 p = 0.041 OR = 0.961 (0.925, 0.998)	β = −0.037 p = 0.069 OR = 0.964 (0.927, 1.003)	β = 0.03 p = 0.237 OR = 1.026 (0.983, 1.0072	β = 0.026 p = 0.260 OR = 1.027 (0.981, 1.075)	β = 0.005 p = 0.795 OR = 1.005 (0.966, 1.047)	β = 0.023 p = 0.272 OR = 1.023 (0.982, 1.065)
Sex	β = 0.630 p = 0.106 OR = 1.877 (0.874, 4.033)	β = −0.160 p = 0.690 OR = 0.852 (0.389, 1.87)	β = 2.45 p < 0.001 OR = 11.6 (3.8, 35.2)	β = 0.760 p = 0.098 OR = 2.138 (0.868, 5.265)	β = 0.478 p = 0.232 OR = 1.613 (0.737, 3.53)	β = 0.884 p = 0.031 OR = 2.42 (1.085, 5.399)
BMI	β = −0.088 p = 0.054 OR = 0.916 (0.837, 1.001)	β = 0.104 p = 0.009 OR = 1.109 (1.026, 1.199)	β = −0.16 p = 0.007 OR = 0.852 (0.759, 0.957)	β = −0.006 p = 0.893 OR = 0.994 (0.908, 1.088)	β = −0.133 p = 0.015 OR = 0.876 (−0.787, 0.975)	β = −0.047 p = 0.283 OR = 0.954 (0.875, 1.039)
Preoperative Harris Hip Score	β = 0.020 p = 0.176 OR = 1.020 (0.991, 1.050)	β = −0.055 p = 0.002 OR = 0.946 (0.913, 0.981)	β = 0.010 p = 0.477 OR = 1.011 (0.982, 1.04)	β = −0.035 p = 0.042 OR = 0.965 (0.933, 0.999)	β = −0.025 p = 0.135 OR = 0.976 (0.944, 1.008)	β = −0.042 p = 0.012 OR = 0.959 (0.929, 0.991)

Coefficients (p value) and ORs (OR) with 95% confidence intervals are shown. Shaded boxes highlight $p < 0.05$.

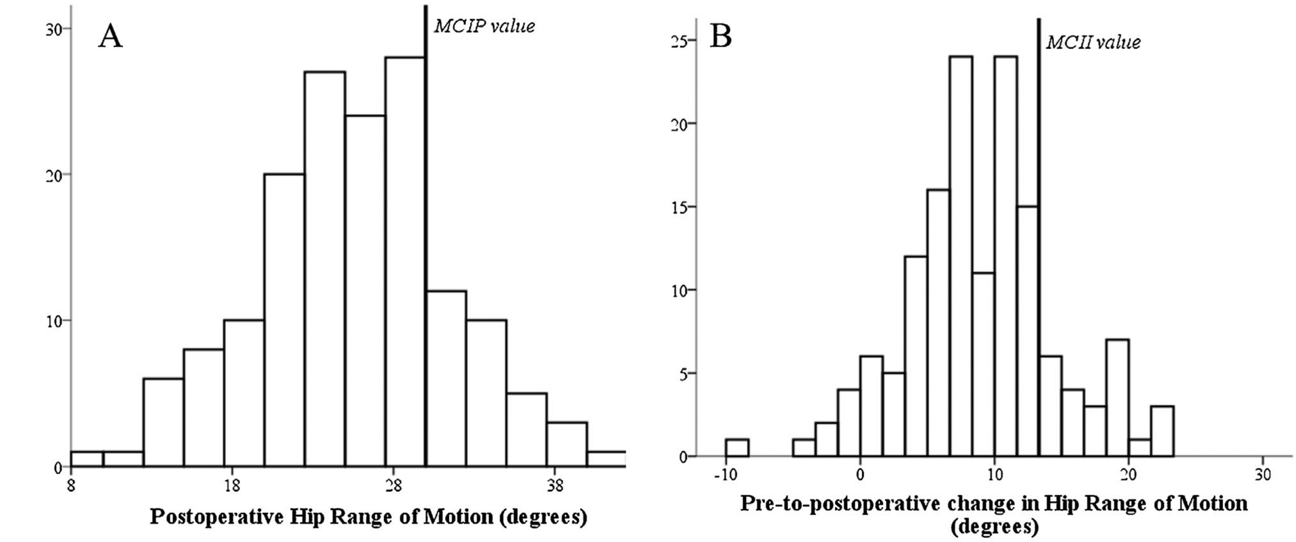

Figure 4. (A) Histogram of the postoperative dynamic sagittal plane hip range of motion (HROM). Vertical line indicates the minimum clinically important postoperative value. (B) Histogram of the preoperative-to-postoperative change in dynamic sagittal plane HROM. Vertical line indicates the minimum clinically important improvement (MCII) for HROM.

(Table 1). Only preoperative HHS was associated with attaining an MCII for HROM (Table 1).

Peak Hip Adduction Moment

The peak hip adduction moment did not significantly improve after THA on average ($p = 0.359$). Preoperative adduction moments were 3.39 ± 1.1%BWH and postoperative adduction moments were 3.43 ± 0.96% BWH. Although the average change was near zero (0.04 ± 1.15% BWH), the change values ranged from -2.68 to 3.99% BWH. The MCIP for the hip adduction moment was 4.15% BWH (3.95% BWH, 4.35% BWH), and was attained by 20.7% (14.5%, 27.6%) of subjects (Fig. 6A). The MCII for hip adduction moment was 0.87% BWH (0.57% BWH, 1.17% BWH) and was attained by 22.8% (15.9%, 30.3%) (Fig. 6B). Again, preoperative hip adduction moments were higher for subjects who did not attain the MCII, but postoperative moments were lower (Fig. 7). Lower BMI, but not sex or HHS, was associated with achieving the MCIP for hip adduction moment (Table 1). Sex was associated with odds of attaining the MCII (Table 1); 31% of women attained the MCII compared to only 16% of men. People who did not achieve the MCII for the adduction moment also had higher preoperative HHS than those who did (58.2 ± 13.6 vs. 51.5 ± 14.4). Age and BMI were not associated with having an MCII (Table 1).

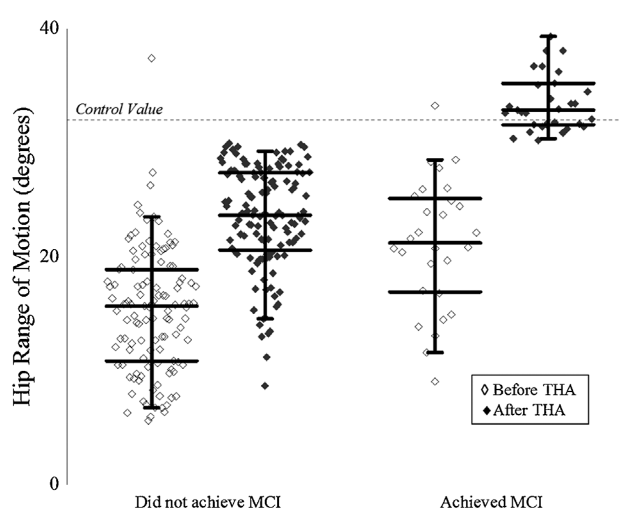

Figure 5. Dot plots illustrating the preoperative and postoper-

DISCUSSION

There were four main contributions of this work. First, this study presented a novel approach to determining benchmarks for gait improvement that are both clinically appropriate and patient-attainable. Second, preliminary benchmarks were established for three key gait variables, normal walking speed, the sagittal plane hip range of motion, and the peak external hip adduction moment. Third, this study began to establish the prevalence of these clinically important gait deficits. Finally, several potential risk factors for failing to achieve the benchmarks were identified.

We and others have previously demonstrated that higher walking speeds or more postoperative improvement in walking speeds are associated with better clinical outcomes or more improvement in clinical outcomes.[20,37,38] This study further demonstrated that a postoperative speed of at least 1.3 m/s could be considered clinically important. This speed benchmark has real-life relevance, as it is approximately the speed required for safe street crossing in an urban area.[39] It should also be noted that this preferred walking speed in the lab may be slightly (~0.2 m/s) higher that the habitual normal speed measured in real life settings, possibly due to behavioral factors in the testing

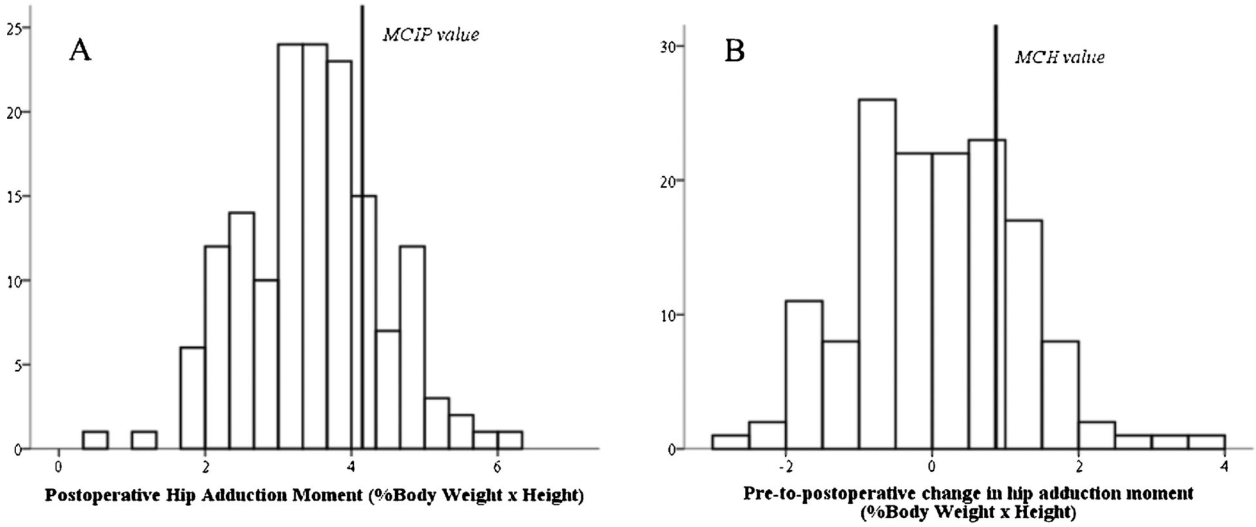

Figure 6. (A) Histogram of the postoperative peak external hip adduction moment. Vertical line indicates the minimum clinically important postoperative value. (B) Histogram of the preoperative-to-postoperative change in hip adduction moment. Vertical line indicates the MCII.

setting.[40] Therefore this speed benchmark may reflect a likely real-world speed of ~1.1 m/s; this is on the low end of the range of speeds associated with independence in activities of daily living, later hospitalization, and fall-related adverse events.[41] Having benchmarks for walking speed is attractive because speed can be measured outside of a gait lab setting without specialized equipment, and because walking speed has relevance for the health of older adults beyond any association with THA outcomes.

A sagittal plane HROM of at least 30° and a postoperative hip adduction moment of 4.2%BWH can be considered clinically important. This postoperative HROM was just below the range of normal values reported both in the literature (31–52°),[18] and in our previous work.[29,32] The clinically important hip adduction moment was also at the low end of the values for

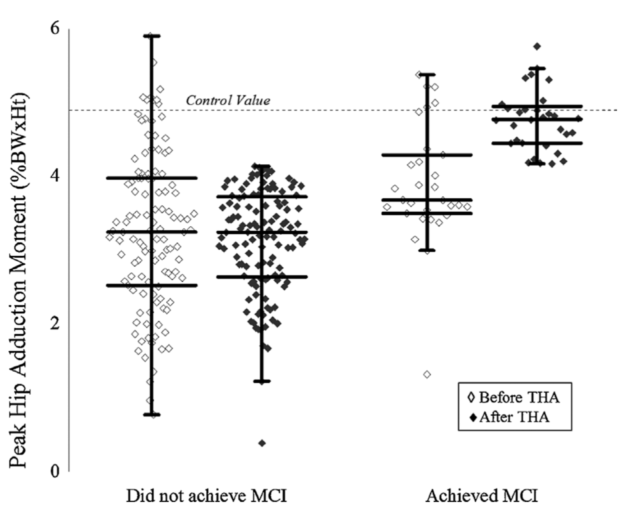

Figure 7. Dot plots illustrating the preoperative and postoperative values of the hip adduction moment for subjects who attained an MCII for this variable and those who did not.

controls that we have previously reported (4.0 ± 0.8% BWH to 4.8 ± 0.9%BWH).[29,32] This suggests that somewhat normal gait should indeed be a goal of THA and supports the notion that more effective rehabilitation interventions targeting these aspects of gait are needed. For range of motion, the minimum clinically important improvement was only 4° higher than the average improvement. This suggests that only minor adjustments in current rehabilitation protocols, with increased focus on flexibility in the sagittal plane, may be needed to reap significant additional benefits. The average hip adduction moment change was substantially lower than the minimum clinically important improvement; thus wider evaluation and adoption of those interventions that have shown promise,[42] or new abductor-focused interventions may be needed. Gait analysis can be a useful way of quantifying dynamic muscle function during walking; the present study can aid future investigations by providing recovery targets for these important gait variables.

It is important to note that although this analysis showed that ~80% of subjects failed to have a clinically important response with respect to gait variables of interest, it is not the case that these subjects necessarily had poor clinical or functional outcomes overall. Indeed, 24% had the maximum possible score (HHS = 100) and 38% had the maximum possible HHS function subscore. However recent reports, for example a recent study from Singh & Lewallen using data from the Mayo Clinic Total Joint Registry which showed that over 25% of patients have moderate to severe limitations in walking and other important activities of daily living 2–5 years after THA,[6] demonstrate that there is room for improvement. We have previously shown that improvement in sagittal plane HROM and dynamic abductor function are associated with improvement in clinical scores.[20] The low response rate for HROM and the hip adduction moment in this study confirms that these are important potential targets for new rehabilitation efforts, and for the first time provides some benchmarks for improvement.

Preoperative patient factors associated with having a meaningful gait response to THA were similar to the predictors of having a meaningful clinical response to THA that have been described in the literature. Younger age was associated with attaining the MCIP for walking speed, but not any of the other variables. This may reflect the inverse relationship between age and gait speed seen in older adults with physical impairment.[9,41,43] Patients with worse preoperative clinical scores typically have more postoperative improvement in these same scores, but worse final outcomes.[27,44] In this study, worse preoperative HHS were associated with higher odds of attaining a minimally clinically important improvement for both hip range of motion and the adduction moment mirrors. The odds of achieving a meaningful final outcome of these variables, however, were not influenced by baseline scores. The literature is mixed on the relationship between BMI and clinical outcomes. A few studies have reported that patients with higher BMIs gain more from THA than those with lower BMIs, but still have poorer final clinical and functional outcomes.[28] Other studies have reported no association between BMI and clinical improvement.[44,45] The present study is generally in line with the literature. Higher BMI was associated with worse odds of passing the clinically meaningful threshold for postoperative range of motion and hip adduction moments, but was not associated with change in these gait variables. This contributes to the consensus that patients with high BMIs obtain significant benefits from THA, but may need additional intervention to achieve optimal results.

Many studies statistically adjust for potential sex effects on THA outcomes without reporting the presence or absence of sex difference. Where the relationship between sex and THA outcomes is specifically discussed, however, results vary. For example, while Nilsdotter and colleagues reported that no sex associations between change in WOMAC function scores two years after THA,[26] others have reported that women experience less recovery of physical function scores compared to men.[44,45] In the present study, female sex was associated with higher odds of having a minimum clinically important improvement in both range of motion and the hip adduction moment, but there was no association between sex and the final outcome threshold for these variables. Still to be determined, however, is whether or not men and women should have the same targets for gait outcomes. Two separate studies have shown that healthy women have higher hip adduction moments than healthy men, and attributed this to anatomical differences.[33,46] Accordingly, perhaps, women should be expected to reach higher values of the hip adduction moment than men after THA. This, in turn, suggests in the present study, men may actually have been more likely, rather than less likely, to reach their clinically meaningful hip adduction moment than the women. More work investigating potential sex differences in THA functional outcomes is needed.

Despite its strengths, which include a large sample size relative to most THA gait studies,[18] and the novel approach to identifying meaningful gait benchmarks, this study has several important limitations. These limitations largely concern the properties of the HHS. First, in outcomes research, minimum clinically important improvement is determined by anchoring relative change in a patient reported outcome measure to a patient acceptable symptom state (PASS).[47] The PASS is identified by directly asking a question such as whether or not the patient is satisfied with his or her current status or whether or not the patient feels “well”. An HHS of 80 or above is typically considered a “good” clinical outcome,[34] but whether or not this score is associated with achieving a PASS has not been studied. The HHS is also a legacy instrument with ceiling effects that may keep it from capturing important higher levels of function,[48] that may be important to contemporary patients. This means that it is possible that the gait benchmarks anchored to an HHS value of 80 may be too conservative for patients with higher functional demands. It has been suggested that patients with lower function may require more relative improvement in order to be satisfied with their treatment outcomes than those with higher preoperative function.[49] Conversely, patients with higher preoperative function may need to reach higher absolute levels of function postoperatively in order to be satisfied.[50] It may be necessary to consider preoperative gait or preoperative clinical scores when determining benchmarks gait improvement. Another limitation is that there are other perioperative factors that could affect gait outcomes, and potentially the benchmarks that would be calculated. These include surgical approach, rehabilitation approaches, implant type, implant positioning and others. However because it is reasonable that all patients should be able to expect some minimum level of functional improvement, it was appropriate to conduct this preliminary analysis with a heterogeneous subject group.

In conclusion, through a novel approach borrowed from outcomes research and not previously used with gait data, this study introduced a new method for establishing clinically relevant gait improvement benchmarks after THA, and identified preliminary MCIP and MCII benchmarks for three key gait variables. MCIP values were calculated for walking speed (1.34 m/s), sagittal plane dynamic hip range of motion (30.0°), and the peak external hip adduction moment (4.2% BWH). MCIP for speed was associated with younger age; MCIP for hip range of motion was associated with female sex, and lower BMI; MCIP for adduction moment was associated with lower BMI. MCII values were also calculated for walking speed (0.32 m/s), range of motion (13.3°), and the peak adduction moment 0.87% BWH. MCII for speed was associated with higher BMI and lower preoperative HHS; MCII for hip range of motion was associated with lower preoperative HHS; finally MCII for adduction moment was associated with female sex and lower preoperative HHS. Further validation of these and other gait benchmarks will expand the potential for wider clinical use of gait analysis in the THA population. On a small scale, gait analysis has already shown to be a useful tool for outcomes assessment and rehabilitation planning after THA.[51] Having meaningful benchmarks can expand its potential for wider use. This work represents an important step in advancing THA gait and rehabilitation research by providing a framework for identifying meaningful benchmarks for improvement. Future prospective studies, using contemporary PROs, other conceptualizations of recovery, and investigating the effect of other patient factors, can build on this framework.

AUTHOR'S CONTRIBUTIONS

KCF conducted the research design, data analysis, and manuscript composition.

ACKNOWLEDGMENTS

This study was funded by a grant from the Rush Research Mentoring Program Young Investigator Research Fund. The sponsors had no role in the study design, data collection, analysis, interpretation, or writing. Data acquisition assistance was provided by Gary Farkas B.S., and Robert Trombley, B.S.

REFERENCES

1. Kurtz SM, Lau E, Ong K, et al. 2009. Future young patient demand for primary and revision joint replacement: national projections from 2010 to 2030. Clin Orthop Relat Res 467:2606–2612.
2. Kurtz S, Ong K, Lau E, et al. 2007. Projections of primary and revision hip and knee arthroplasty in the united states from 2005 to 2030. J Bone Joint Surg Am 89:780–785.
3. Hobbs N, Dixon D, Rasmussen S, et al. 2011. Patient preoperative expectations of total hip replacement in european orthopedic centers. Arthritis Care Res (Hoboken) 63:1521–1527.
4. Heiberg KE, Ekeland A, Mengshoel AM. 2013. Functional improvements desired by patients before and in the first year after total hip arthroplasty. BMC Musculoskelet Disord 14: 243–2474–14–243.
5. Mancuso CA, Jout J, Salvati EA, et al. 2009. Fulfillment of patients' expectations for total hip arthroplasty. J Bone Joint Surg Am 91:2073–2078.
6. Singh JA, Lewallen DG. 2013. Patient-level clinically meaningful improvements in activities of daily living and pain after total hip arthroplasty: data from a large US institutional registry. Rheumatology (Oxford) 52:1108–1118.
7. Judge A, Cooper C, Williams S, et al. 2010. Patient-reported outcomes one year after primary hip replacement in a european collaborative cohort. Arthritis Care Res (Hoboken) 62:480–488.
8. Hawker GA, Badley EM, Borkhoff CM, et al. 2013. Which patients are most likely to benefit from total joint arthroplasty? Arthritis Rheum 65:1243–1252.
9. Bennett D, Humphreys L, O'Brien S, et al. 2008. Gait kinematics of age-stratified hip replacement patients-a large scale, long-term follow-up study. Gait Posture 28:194–200.
10. Beaulieu ML, Lamontagne M, Beaule PE. 2010. Lower limb biomechanics during gait do not return to normal following total hip arthroplasty. Gait Posture 32:269–273.
11. Lugade V. 2010. Gait asymmetry following an anterior and anterolateral approach to total hip arthroplasty. Clin Biomech 25:675–680.
12. Horstmann T, Listringhaus R, Haase GB, et al. 2013. Changes in gait patterns and muscle activity following total hip arthroplasty: a six-month follow-up. Clin Biomech (Bristol, Avon) 28:762–769.
13. Queen RM, Schaeffer JF, Butler RJ, et al. 2013. Does surgical approach during total hip arthroplasty alter gait recovery during the first year following surgery?. J Arthroplasty 28:1639–1643.
14. Agostini V, Ganio D, Facchin K, et al. 2014. Gait parameters and muscle activation patterns at 3, 6 and 12 months after total hip arthroplasty. J Arthroplasty 29:1265–1272.
15. Queen RM, Appleton JS, Butler RJ, et al. 2014. Total hip arthroplasty surgical approach does not alter postoperative gait mechanics one year after surgery. PM R 6:221–226. quiz 226.
16. Li J, McWilliams AB, Jin Z, et al. 2015. Unilateral total hip replacement patients with symptomatic leg length inequality have abnormal hip biomechanics during walking. Clin Biomech 30:513–519.
17. Foucher KC, Freels S. 2015. Preoperative factors associated with postoperative gait kinematics and kinetics after total hip arthroplasty. Osteoarthritis Cartilage doi: 10.1016/j.joca.2015.05.005. [Epub ahead of print]
18. Ewen AM, Stewart S, St Clair Gibson A, et al. 2012. Postoperative gait analysis in total hip replacement patients-a review of current literature and meta-analysis. Gait Posture 36:1–6.
19. Kolk S, Minten MJM, Van Bon GEA, et al. 2014. Gait and gait-related activities of daily living after total hip arthroplasty: a systematic review. Clin Biomech 29:705–718.
20. Behery OA, Foucher KC. 2014. Are harris hip scores and gait mechanics related before and after THA?. Clin Orthop Relat Res 472:3452–3461.
21. Eitzen I, Fernandes L, Kallerud H, et al. 2015. Gait characteristics, symptoms and function in persons with hip osteoarthritis: a longitudinal study with 6–7 years follow-up. J Orthop Sports Phys Ther 1–28.
22. Lenaerts G, De Groote F, Demeulenaere B, et al. 2008. Subject-specific hip geometry affects predicted hip joint contact forces during gait. J Biomech 41:1243–1252.
23. Foucher KC, Hurwitz DE, Wimmer MA. 2009. Relative importance of gait vs. joint positioning on hip contact forces after total hip replacement. J Orthop Res 27:1576–1582.
24. Weber T, Dendorfer S, Dullien S, et al. 2012. Measuring functional outcome after total hip replacement with subject-specific hip joint loading. Proc Inst Mech Eng Part H J Eng Med 226:939–946.
25. Tubach F, Ravaud P, Baron G, et al. 2005. Evaluation of clinically relevant changes in patient reported outcomes in knee and hip osteoarthritis: the minimal clinically important improvement. Ann Rheum Dis 64:29–33.
26. Nilsdotter AK, Petersson IF, Roos EM, et al. 2003. Predictors of patient relevant outcome after total hip replacement for osteoarthritis: a prospective study. Ann Rheum Dis 62:923–930.

27. Judge A, Arden NK, Batra RN, et al. 2013. The association of patient characteristics and surgical variables on symptoms of pain and function over 5 years following primary hip-replacement surgery: a prospective cohort study. BMJ Open 3:DOI: 10.1136/bmjopen–2012–002453.
28. Judge A, Batra RN, Thomas GE, et al. 2014. Body mass index is not a clinically meaningful predictor of patient reported outcomes of primary hip replacement surgery: prospective cohort study. Osteoarthritis Cartilage 22:431–439.
29. Foucher KC, Wimmer MA, Moisio KC, et al. 2011. Time course and extent of functional recovery during the first postoperative year after minimally invasive total hip arthroplasty with two different surgical approaches-a randomized controlled trial. J Biomech 44:372–378.
30. Hurwitz DE, Foucher KC, Sumner DR, et al. 1998. Hip motion and moments during gait relate directly to proximal femoral bone mineral density in patients with hip osteoarthritis. J Biomech 31:919–925.
31. Andriacchi TP, Natarajan RN, Hurwitz DE. 2005. Musculoskeletal dynamic locomotion and clinical applications. In: Mow VC, Huiskes R, editors. Basic orthopaedic biomechanics and mechano-biology, 3rd ed. Philadelphia: Lippincott. p 91–121.
32. Foucher KC, Hurwitz DE, Wimmer MA. 2007. Preoperative gait adaptations persist one year after surgery in clinically well-functioning total hip replacement patients. J Biomech 40:3432–3437.
33. Moisio KC, Sumner DR, Shott S, et al. 2003. Normalization of joint moments during gait: a comparison of two techniques. J Biomech 36:599–603.
34. Soderman P, Malchau H. 2001. Is the harris hip score system useful to study the outcome of total hip replacement?. Clin Orthop Relat Res (384) 189–197.
35. Arden NK, Kiran A, Judge A, et al. 2011. What is a good patient reported outcome after total hip replacement?. Osteoarthritis Cartilage 19:155–162.
36. Keurentjes JC, Van Tol FR, Fiocco M, et al. 2014. Patient acceptable symptom states after totalhip or knee replacement at mid-term follow-up: thresholds of the oxford hip and knee scores. Bone Joint Res 3:7–13.
37. Boardman DL, Dorey F, Thomas BJ, et al. 2000. The accuracy of assessing total hip arthroplasty outcomes: a prospective correlation study of walking ability and 2 validated measurement devices. J Arthroplasty 15:200–204.
38. Unnanuntana A, Mait JE, Shaffer AD, et al. 2012. Performance-based tests and self-reported questionnaires provide distinct information for the preoperative evaluation of total hip arthroplasty patients. J Arthroplasty 27:770–775. e1.
39. Robinett CS, Vondran MA. 1988. Functional ambulation velocity and distance requirements in rural and urban communities. A clinical report. Phys Ther 68:1371–1373.
40. Foucher KC, Thorp LE, Hildebrand M, et al. 2010. Differences in preferred walking speeds in a gait lab compared to the “real world” after total hip replacement. Arch Phys Med Rehabil 91:1390–1395.
41. Middleton A, Fritz SL, Lusardi M. 2015. Walking speed: the functional vital sign. J Aging Phys Act 23:314–322.
42. Di Monaco M, Castiglioni C. 2013. Which type of exercise therapy is effective after hip arthroplasty? A systematic review of randomized controlled trials. Eur J Phys Rehabil Med 49:893–907. quiz 921–3.
43. Peel NM, Kuys SS, Klein K. 2013. Gait speed as a measure in geriatric assessment in clinical settings: a systematic review. J Gerontol A Biol Sci Med Sci 68:39–46.
44. Judge A, Javaid MK, Arden N, et al. 2012. A clinical tool to identify patients who are most likely to receive long term improvement in physical function after total hip arthroplasty. Arthritis Care Res (Hoboken) 64:881–889.
45. Cushnaghan J, Coggon D, Reading I, et al. 2007. Long-term outcome following total hip arthroplasty: a controlled longitudinal study. Arthritis Care Res 57:1375–1380.
46. Boyer KA, Beaupre GS, Andriacchi TP. 2008. Gender differences exist in the hip joint moments of healthy older walkers. J Biomech 41:3360–3365.
47. Paulsen A, Roos EM, Pedersen AB, et al. 2013. Minimal clinically important improvement (MCII) and patient-acceptable symptom state (PASS) in total hip arthroplasty (THA) patients 1 year postoperatively. Acta Orthop 85:39–48.
48. Wamper KE, Sierevelt IN, Poolman RW, et al. 2010. The harris hip score: do ceiling effects limit its usefulness in orthopedics?. Acta Orthop 81:703–707.
49. Tubach F, Dougados M, Falissard B, et al. 2006. Feeling good rather than feeling better matters more to patients. Arthritis Rheum 55:526–530.
50. Noble PC, Dwyer M, Brekke A. 2013. Commonalities, differences, and challenges with patient-derived outcome measurement tools: function/activity scales. Clin Orthop 471: 3457–3465.
51. Bhave A, Marker DR, Seyler TM, et al. 2007. Functional problems and treatment solutions after total hip arthroplasty. J Arthroplasty 22:116–124.