Gait, Quality of Life, and their Association Following Total Hip Arthroplasty

Martha Macht Sliwinski, PT, PhD;[1] Sue Ann Sisto, PT, PhD[2]

[1] Columbia University, Physical Therapy Program, New York, NY
[2] Kessler Medical Rehabilitation Research and Education Corporation, Associate Professor, Physical Medicine and Rehabilitation, UMDNJ/NJMS

ABSTRACT

Purpose: Total hip arthroplasty (THA) surgery is one of the most common orthopedic procedures performed on individuals with end-stage osteoarthritis of the hip. This study: (1) compared temporal spatial gait parameters and quality of life (QOL) scores of individuals with unilateral total hip arthroplasty (THA) to those of healthy older adults ages 65 to 85 years and (2) explored the relationship between the variables. **Methods:** Three dimensional motion analysis was used to calculate walking velocity, cadence, stride length, single support time, and double support time. All participants completed the Medical Outcome Survey Short Form 36 Health Survey (SF 36®) to measure health related QOL subscales. **Results:** The individuals with THA walked slower ($P = .005$) with a longer double support phase ($P = .02$) and rated physical functioning ($P < .0001$) and role physical scores ($P = .001$) lower than the healthy older adults. For all subjects combined, a positive correlation was identified between walking velocity and physical functioning ($P = .001$), role-physical scores ($P = .001$) and bodily pain ($P = .001$); a negative correlation was identified between double support time and role physical score ($P = .002$) and bodily pain ($P = .002$). **Conclusion:** Individuals who undergo THA surgery have gait deficits that relate to physical subscales of the SF36®. These findings provide guidance for physical therapy interventions focused on gait performance after THA.

Key Words: total hip arthroplasty, quality of life, gait, geriatrics, physical therapy

INTRODUCTION

Total hip arthroplasty (THA) surgery is one of the most common orthopedic procedures; 168,000 THA surgeries were performed in the United States in 1999.[1] Individuals with end-stage osteoarthritis of the hip have documented walking problems and seek THA surgery for relief of pain and improved mobility.[1-6] Improved functional recovery, quality of life (QOL), and decreased pain following THA surgery are well documented.[7-11] Recovery of normal walking velocity and limb symmetry remains controversial as reported in studies of individuals 3 to12 months postsurgery.[12-17] Currently, the average length of stay in an acute care hospital for elective unilateral THA is 3 to 5 days and may not necessarily be followed by further physical therapy in an acute rehabilitation facility, subacute rehabilitation facility, out-patient setting, or at home.[9,10,16] The American Physical Therapy Association has documented the prognosis for rehabilitation from a joint replacement for 80% of the patients without surgical complications to be within a 6-month period with the range of 12 to 60 treatments. When engaging in gait training interventions, physical therapists should also consider health-related QOL when evaluating treatment effectiveness.

Health-related QOL as rated on the Medical Outcome Survey Short Form 36-item Health Survey (SF 36®) has been used to examine the outcomes of THA through pre- and postsurgery assessments.[7-9,11] Jones et al[10] compared SF 36® scores to general population data in the existing literature; however, the authors did not compare their results to an age-matched control group.

The purposes of this investigation were to: (1) compare temporal spatial gait parameters of individuals following unilateral THA to healthy controls, ages 65-85, (2) compare scores on the SF 36® between these 2 groups, and (3) test for relationships between temporal spatial gait parameters and SF 36® QOL subscales across groups.

METHODS

This study applied a cross-sectional design with a convenience sample of 32 individuals. Half of the participants underwent a THA and were compared to a healthy control group. Study approval was granted by the Institutional Review Board of The Kessler Medical Rehabilitation Research and Education Corporation, and by the Institutional Review Board of New York University. All participants read and signed the institution approved consent form prior to data collection.

Address correspondence to: Martha Macht Sliwinski, Columbia University, Physical Therapy Program, 710 W. 168th Street, 8th Floor, New York, NY 10027, Ph: 212-305-3688, Fax: 212-305-4569 (ms2184@columbia.edu).

Participants

Thirty-two volunteers, ages ranging from 65 to 85 years and walking without an assistive device, participated in the study. The participants were recruited from the New Jersey and Pennsylvania area via institution approved flyers posted within the institution's physical therapy departments and distributed to potential study participants by individual physical therapists. Participants with THA fulfilled the following inclusion criteria: history of osteoarthritis, minimum of 2 months post THA, full weight bearing status, no other lower limb musculoskeletal diagnosis, and completion of formal rehabilitation. Individuals volunteering for the healthy group fulfilled the following inclusion criteria: no history of joint arthroplasty or chronic musculoskeletal problems in the lower limbs. Participants were excluded if they: had 2 or more falls within the past month, experienced a new cardiac or neurological condition within the past 6 months, had severe osteoporosis, or took prescribed medications causing dizziness (to avoid the confound of other system failure).[17] Age, weight, height, and lower-limb length were recorded for all participants. Additionally, body mass index was calculated using weight and height.

Gait Analysis

Gait analysis was conducted using the Vicon™ Motion Analysis System (Workstation version 3.0), an infrared camera system designed to record 3D human motion. This system has demonstrated good reliability both within and between test days.[19] A Vicon™ standard 27 marker set was used as was a sampling frequency of 120 Hz. Participants completed 10 normal walking speed trials with their typical walking shoes on the 30-foot walkway. The first 3 trials having the most optimal marker visibility were processed, averaged, and used for data analysis. Vicon™ Clinical Manager Software was used to calculate temporal spatial gait parameters including: velocity, stride length, cadence, single support time, and double support time.

Quality of Life Measure

Each participant completed the SF 36® developed by Ware, a self-assessment questionnaire of health-related QOL.[20] There are 8 subscales represented in the SF 36®: physical functioning, role physical, bodily pain, general health, vitality, social functioning, role-emotional, and mental health. Reliability has been documented for all 8 subscales (coefficients = .68 to .93).[20] Additionally, content validity and criterion validity have been established and published for the SF-36®.[20] The procedure for scoring the SF36® was followed according to Ware,[20] the raw scores for each subscale are transformed to yield a score between 0 to 100. This transformed score represents the percentage of the total score possible for each subscale.[20] The score range represents 0 as the lowest and 100 represents the highest QOL.[20] The SF-36® is most commonly examined in 2 ways, either through mental and physical component scores or by the 8 subscales individually. [20] For the purposes of this study the SF-36® was evaluated using the 8 subscale approach.

Statistical Methods

All data analysis was conducted using SPSS version 11.0 for Windows (SPSS Inc, Chicago, Ill). Participant demographic characteristics were summarized using conventional descriptive statistics. Gait parameters were examined through 2 statistical tests. First, a one-way multivariate analysis of variance (MANOVA) was conducted to test for differences between sides in lower limb temporal spatial gait parameters (left versus right lower limb and operated versus non-operated lower limbs). Second a one-way MANOVA was conducted to examine if differences existed in temporal spatial gait parameters between the 2 groups (THA and healthy). A one-way MANOVA was performed to compare SF 36® scores between groups. The alpha level for the MANOVA tests was set at .05. To examine possible relationships between the walking parameters and the SF 36® scores, Pearson Product-Moment Correlations were calculated. The critical alpha level for the correlations was set at .01 to reduce the probability of a Type I error.

RESULTS

Subjects

The study included a group of 16 individuals with unilateral THA, 9 women and 7 men, and a group of 16 healthy older adults, 11 women and 5 men. THA participants completed their outpatient physical therapy in suburban rehabilitation centers of Northern New Jersey. No difference was found between the 2 groups for age, weight, height, lower limb length, and body mass index (Table 1).

Of the individuals with THA, 14 had cemented surgery allowing weight bearing as tolerated immediately postsurgery and 2 had noncemented surgery permitting weight bearing as tolerated by the third or fourth month postsurgery. Ten individuals underwent a left THA and 6 underwent a right THA. Ten of the subjects were tested at 2 to 3 months postsurgery. The 2 individuals with noncemented surgery were tested at 4 and 5 months postsurgery. The remaining 3 subjects that underwent cemented THA surgery were tested at 6 and 7 months postsurgery and 2 years postsurgery.

Gait Parameters

Temporal spatial characteristics are compiled in Table 2. No differences were found between left and right lower limbs or operated and nonoperated lower limbs for any parameter.

Table 1. Subject Characteristics

Group	Gender	Age (years) Mean ± SD	Height (cm) Mean ± SD	Weight (kg) Mean ± SD	Body Mass Index (kg/m²) Mean ± SD
Healthy Older Adults (N=16)	5 Male 11 Female	74.0 ± 5.7	161.4 ± 11.8	70.1 ± 15.7	26.8 ± 4.8
Individuals with THA (N=16)	7 Male 9 Female	70.9 ± 4.2	165.6 ± 8.7	74.6 ± 16.3	27.0 ± 4.3

Table 2. Walking Characteristics for Lower Limb of Each Group

Walking Characteristic	Healthy Group Mean ± SD		THA Group Mean ± SD	
	Left	Right	Operated	Nonoperated
Velocity (m/s)	1.3 ± 0.2	1.3 ± 0.2	1.1 ± 0.2	1.1 ± 0.2
Cadence (steps/min)	112.7 ± 12.5	113.3 ± 13.0	104.9 ± 10.5	104.3 ± 11.1
Stride Length (m)	1.3 ± 0.2	1.3 ± 0.2	1.2 ± 0.1	1.2 ± 0.2
Single Support Time (s)	0.4 ± 0.1	0.4 ± 0.04	0.4 + 0.04	0.4 ± 0.04
Double Support Time (s)	0.4 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.4 ± 0.1

Therefore, the average of the 2 lower limbs was used for the subsequent MANOVA used for the comparison between the groups. The results of the MANOVA for the effect of group on the temporal spatial gait parameters are listed in Table 3. The mean velocity was significantly slower (P = .005) for the THA group (1.1 ± .2 m/s) than for the healthy group (1.3 ± .2 m/s). The cadence of the THA group (104.6 ± 10.8 steps/min) was significantly less (P < .05) than that (113.1 ± 12.7 steps/min) of the healthy group. The step length was also less (1.2 ± .2 m versus 1.3 ± .2 m, P < .05). Double support time was significantly longer (P = .02) for the THA group (.4 ± .2 s) than for the healthy group (.4 ± .1 s). No difference found for single support time between the groups (P = .4, healthy .4 ± .1 s, THA .4 ± .1 s).

Quality of Life

The results of the scores for the SF 36® (Table 4) and MANOVA (Table 5) demonstrated significant differences between the groups for physical functioning and role-physical subscale scores (P = .001). The physical functioning score was 23.8 points lower for the THA group compared to the healthy group and the role-physical score, indicating role limitations due to physical health problems, was 35.9 points lower for the THA group. No differences were found between the 2 groups on any other subscale score. The change in health score reflects the health rating compared to a year ago.[20] The score ranges from 1, much better than a year ago, to 5, much worse than 1 year ago. The scores for the THA group ranged from 'somewhat' to 'much better' compared to the previous year; this would be an expected outcome from THA surgery.

Gait Parameters and SF 36® Relationships

Relationships between gait characteristics and QOL were not significant for either the THA group (Table 6) or the healthy group (Table 7). However, when the groups were combined, some of the relationships between gait characteristics and the 8 subscales were significant (Table 8). The significant correlations indicate that as walking velocity increased scores on the physical functioning, role physical and bodily pain subscales improved. Additionally, role physical and bodily pain subscales declined as double support time increased. The inverse relationship is expected as double support time increases with slower velocities as demonstrated in the findings from this study.

DISCUSSION

Except for a history of unilateral THA, the physical characteristics of the 2 groups studied were relatively homogeneous

Table 3. Results of One-way Multivariate Analysis of Variance Examining the Effect of Group on Temporal Spatial Gait Parameters

Source	df	MS	F	*P*-value
Between Subjects				
Group				
Average Velocity	1	.267	9.246	.005
Average Stride Length	1	.093	4.270	.048
Average Cadence	1	590.820	4.325	.046
Average Single Support Time	1	.001	.787	.382
Average Double Support Time	1	.026	6.471	.016
Error				
Average Velocity	30	.029		
Average Stride Length	30	.022		
Average Cadence	30	136.591		
Average Single Support Time	30	.002		
Average Double Support Time	30	.004		

Table 4. Comparison of SF-36 Subscale Scores between Groups

Subscale	Healthy Group Mean ± SD	THA Group Mean ± SD
Physical Functioning*	91.9 ± 14.5	68.1 ± 17.5
Role- Physical*	93.8 ± 19.4	57.8 ± 36.2
Bodily Pain	87.5 ± 12.8	76.4 ± 19.4
General Health	81.8 ± 12.3	82.0 ± 11.6
Vitality	79.4 ± 15.3	69.7 ± 14.1
Social Functioning	85.4 ± 7.8	79.9 ± 15.8
Role Emotional	93.8 ± 25.0	75.0 ± 37.5
Mental Health	85.4 ± 11.2	79.0 ± 18.1
Change in Health	1.7 ± 0.8	2.7 ± 0.6

*$P \leq .001$

because no significant differences were identified for age, gender, weight, body mass index, height, and lower limb length. Therefore, the results were not significantly influenced by the physical characteristics.

Although the individuals with THA walked slower than the healthy group, in this study their velocity was faster than that reported in the literature (0.67 m/s to 1.02 m/s).[12-14] This difference may be related to our participants being community dwelling adults that drove independently and had active lifestyles. Secondly no one was discharged to a subacute or nursing home facility following THA surgery. Lastly, instrumentation for collecting and calculating gait characteristics vary among laboratories, therefore utilization of a control group is critical for comparing findings.

Walking velocity decreases and the incidence of falls increases with advancing age as mechanisms of postural control deteriorate and medial-lateral balance control strategies decline.[22,23] Cadence and stride length are parameters that can, either together or separately, alter walking velocity.[24] Younger adults tend to decrease walking velocity by decreasing cadence and increasing double support time.[24,25] In contrast, healthy older adults slow their walking velocity by employing a shorter stride

Table 5. Results of One-way Multivariate Analysis of Variance Examining the Effect of Group on Quality of Life

Source	df	MS	F	*P*-value
Between Subjects				
Group				
Physical Health	1	4512.500	17.496	.000
Role Physical	1	10332.031	12.264	.001
Bodily Pain	1	987.679	3.664	.065
General Health	1	.500	.003	.953
Vitality	1	750.781	3.483	.072
Social Functioning	1	246.920	.584	.289
Role Emotional	1	2812.500	2.768	.072
Mental Health	1	264.500	1.166	.289
Error				
Physical Health	30	257.917		
Role Physical	30	842.448		
Bodily Pain	30	269.536		
General Health	30	143.567		
Vitality	30	215.573		
Social Functioning	30	155.864		
Role Emotional	30	1016.219		
Mental Health	30	226.900		

Table 6. Correlations* Between SF-36 Subscale Scores and 5 Gait Parameters among 16 Healthy Individuals

SF 36® Subscale	Velocity	Double Support	Cadence	Stride Length	Single Support
Physical Functioning	.32	.02	.23	.15	- .26
Role Physical	.40	- .09	.20	.25	- .18
Bodily Pain	.45	- .25	.08	.40	.09
General Health	.30	- .09	.16	.16	- .13
Vitality	.09	- .09	- .10	.23	.18
Social Functioning	.25	- .16	.27	.04	- .16
Role Emotional	.43	- .08	.28	.21	- .28
Mental Health	- .22	.04	.02	- .25	.00

*No correlation is significant at $P < .01$

length with a longer time in double support to promote a safe walking pattern. The results of this study demonstrate that individuals with THA decreased their velocity by both a decrease in cadence and stride length with a longer time in double support.

Thus, the differences in the temporal spatial walking parameters between the healthy group and the individuals with THA may have occurred to provide for an increased pattern of stability during self-selected walking velocities for the individuals with THA. Swing phase does not change in duration with alterations in walking velocity in the healthy elderly.[25] Perron et al reported single support time for persons with THA at an

Table 7. Correlations* Between SF-36 Subscale Scores and 5 Gait Parameters among 16 Patients with Total Hip Arthroplasties

SF 36® Subscale	Velocity	Double Support	Cadence	Stride Length	Single Support
Physical Functioning	.45	-.40	.44	.31	-.36
Role Physical	.46	-.50	.42	.30	-.20
Bodily Pain	.50	.55	.41	.37	-.10
General Health	.59	-.50	.61	.52	-.25
Vitality	.57	.61	.30	.31	-.50
Social Functioning	.31	.42	.30	.16	-.21
Role Emotional	.09	-.09	-.33	.44	.46
Mental Health	.50	-.43	.27	.47	-.05
*No correlation is significant at $P<.01$					

Table 8. Correlations* Between SF-36 Subscale Scores and 5 Gait Parameters among 32 Individuals (16 healthy & 16 with total hip arthroplasty)

SF 36® Subscale	Velocity	Double Support	Cadence	Stride Length	Single Support
Physical Functioning	.57**	-.43	.46	.39	-.35
Role Physical	.58**	-.52*	.44	.39	-.23
Bodily Pain	.57**	-.53*	.34	.44	-.07
General Health	.39	-.28	.27	.29	-.18
Vitality	.44	.40	.30	.35	-.15
Social Functioning	.35	.40	.32	.17	-.20
Role Emotional	.32	-.09	.52	.39	.07
Mental Health	.30	-.34	.28	.20	-.06
* $P = .002$ (2- tailed) ** $P = .001$ (2- tailed)					

early postsurgical time period that were similar to those in this study.[26] Therefore, single support time does not appear to play a role in the adaptation of gait over time in this population. Our findings are consistent with the literature that individuals chose to decrease velocity and make adaptations during the double support phase of walking versus those made in swing.[24-28]

The lower physical functioning score for individuals with THA compared to the healthy group indicated that the individuals with THA perceived themselves as more limited in performing everyday activities in comparison to the healthy group. Jones et al[10] administered the SF 36® 1 month preoperatively and 6 months postoperatively to 208 individuals with THA and found large improvements in physical functioning, role physical, and bodily pain scores but these scores were still below those of the general population, similar to the findings in this study. Therefore, the conclusions from this study comparing ratings on the SF 36® using a control group versus general population scores are statistically more powerful.

The lack of significant differences in bodily pain scores between groups demonstrates a positive outcome of THA surgery. In addition, the individuals with THA noted a marked decrease in pain and improvement in walking as a positive outcome of the surgery. This study outcome provides valuable information for physical therapists.

The role physical scores of the female individuals with THA were lower than those of the men (female = 33.3, male = 83.3). The variability in the overall role physical subscale was due to the women scoring this scale lower. Women with THA may be more affected in their role functioning as a result of THA than men, however, a larger sample would be needed to validate this finding.

Many of the individuals with THA commented while completing the SF 36® that the surgical precautions post THA (limiting the movement of hip flexion to 90°, hip adduction to 0°, and hip internal rotation to 0°) restricted or modified some of their activities. For example, many participants noted difficulty with donning shoes, using a raised toilet seat, and getting in and out of a car while maintaining total hip precautions. Further longitudinal research after the surgeon has lifted THA precautions to determine if a change in physical functioning and role physical is an artifact of surgical restrictions.

The positive correlation identified between walking velocity, physical functioning, role physical, and bodily pain score have important implications for rehabilitation. It is logical that increased walking velocity would improve individuals' perception of their role and actual physical functioning in everyday life. A slower walking speed is the most common compensation employed by the elderly, especially those with mobility limitations.[25,29] A decrease in walking velocity may be indicative of compensatory strategies secondary to a decline in the musculoskeletal or neuromuscular system as well as self-perceived physical ability. Physical therapists should interpret improvements in walking velocity as positively related to how their patients are likely to perceive their role in everyday life. The positive correlation between bodily pain scores and walking velocity is logical. Although no group differences were found between bodily pain scores, the relationship that velocity would decrease as pain increases and increase as pain decreases is expected.

Our study had several limitations. The sample represented individuals from the New Jersey and Pennsylvania area and therefore the results cannot necessarily be generalized to other geographic areas. The individuals with THA were only tested postsurgery; presurgical data would enhance outcome information regarding changes in gait and health-related QOL for physical therapists. Additionally, all of the individuals with THA had further rehabilitation following their in-patient acute care stays both acute rehabilitation and outpatient therapy. Therefore, further research is indicated regarding the number of physical therapy sessions and the setting of physical therapy services. Further, all of the individuals with THA in this study drove and lived in suburban areas, additional research is needed regarding rural and urban environments as gait parameters and health-related QOL maybe affected differently. A larger sample size would be needed to identify within group differences that this study could not address. A larger sample would be indicated to examine the effect that gender may contribute to health-related QOL.

CONCLUSIONS

The findings of this study demonstrate temporal-spatial gait symmetry and bodily pain subscale scores similar to a control group as positive outcomes following THA surgery. Physical therapists should include quality of life questionnaires as part of their documentation to examine the impact of physical therapy interventions on such measures. Identifying physical therapy interventions that improve symmetrical gait velocity may also be effective in enhancing self perceived QOL measures.

ACKNOWLEDGEMENTS

This study was conducted at the Human Performance and Movement Analysis Laboratory (HPMAL) at the Kessler Medical Rehabilitation Research and Education Corporation (KMRREC) and the Henry H. Kessler Foundation in West Orange, New Jersey. The authors would like to thank Quin Bond for his assistance with data collection and processing for the 3D-movement analysis and quality of life survey.

REFERENCES

1. Trudelle-Jackson E. Balance and postoperative lower extremity joint replacement. *Orthop Phys Ther Clin N Am.* 2002;11:101-109.
2. Walker WC, Keyser-Marcus LA, Cifu DX, Chaudhri M. Inpatient interdisciplinary rehabilitation after total hip arthroplasty: a comparison of revision and primary total hip arthroplasty. *Arch Phys Med Rehabil.* 2001;82:129-133.
3. Tesio L, Civashi P, Tessari L. Motion of the center of gravity of the body in clinical evaluation of gait. *Am J Phys Med.* 1985;64:57.
4. Wadsworth JB, Smidt GL, Johnston RC. Gait characteristics of subjects with hip disease. *Phys Ther.* 1972;52:829-837.
5. Lafuente R, Belda JM, Sánchez-Lacuesta J, Soler C, Proveda R, Prat J. Quantitative assessment of gait deviation: contribution to the objective measurement of disability. *Gait Posture.* 2000;11:191-198.
6. Winter DA, Olney SJ, Conrad SC, White SC, Ounpuu S, Gage JR. Adaptability of motor patterns in pathological gait. In: Winters JM, Woo SL-Y, eds. *Multiple Muscle Systems: Biomechanics and Movement Organization.* New York, NY: Springer-Verlag; 1990:686.
7. Boardman DL, Dorey F, Thomas BJ, Lieberman JR. The accuracy of assessing total hip arthroplasty outcomes: a prospective correlation study of walking ability and 2 validated measurement devices. *J Arthroplasty.* 2000;2:200-204.

8. Chiu H, Chern J, Shi H, Chen SH, Chang JK. Physical Functioning and health-related quality of life: before and after total hip replacement. *Kaohsiung J Med Sci*. 2000;16:285-292.
9. Gilbey HJ, Ackland TR, Wang AW, Morton AR, Trouchet T, Tapper J. Exercise improves early functional recovery after total hip arthroplasty. *Clin Orthop Rel Res.* 2003;408:193-200.
10. Jones AC, Voaklander DC, Johnston WC, Suarez-Almazor ME. Health related quality of life outcomes after total hip and knee athroplasties in a community based population. *J Rheumatol.* 2000;27:1745-1752.
11. March LM, Cross MJ, Lapsley H, et al. Outcomes after hip or knee replacement surgery for osteoarthritis. *Med J Austr.* 1999;71:235-238.
12. Perrin T, Dorr LD, Perry J, Gronley J, Hull DB. Functional evaluation of total hip arthroplasty with five- to ten-year follow-up evaluation. *Clin Orthop Rel Res.* 1985;195:252-259.
13. Wall JC, Ashburn A, Klenerman L. Gait analysis in the assessment of functional performance before and after total hip replacement. *J Biomech Eng.* 1981;3:121-127.
14. Berman AT, Quinn RH, Zarro VJ. Quantitative gait analysis in unilateral and bilateral total hip replacements. *Arch Phys Med Rehabil.* 1991;72:190-194.
15. Loizeau J, Allard P, Eng P, Duhaime M, Landerjerit B. Bilateral gait patterns in subjects fitted with total hip prothesis. *Arch Phys Med Rehabil.* 1995;76:552-557.
16. Weingarten S, Riedinger MS, Sandhu M, et al. Can practice guidelines safely reduce hospital length of stay? Results from a multicenter interventional study. *Am J Med.* 1998;105:33-40.
17. Sattin RW. Falls among older persons: a public health perspective. *Annu Rev Public Health.* 1992;13:489-508.
18. APTA. Guide to physical therapy practice. *Phys Ther.* 2001:265.
19. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic and electromyographic data in normal adult gait. *J Orthop Res.* 1989;76:849-860.
20. Ware JE. SF-36 *Health Survey Manual and Interpretation Guide.* Boston, Mass: Nimrod Press; 2000.
21. Baechle TR, ed. *Essentials of Strength Training and Conditioning.* Champaign, Ill: Human Kinetics; 1994.
22. Tinetti ME, Williams CS. The effect of falls and fall injuries on functioning in community-dwelling older persons. *J Gerontol A Biol Sci Med Sci.* 1998;53A:M112-M119.
23. Maki BE, Edmondstone MA, McIlroy WE. Age-related differences in laterally directed compensatory stepping behavior. *J Gerontol A Biol Sci Med Sci.* 2000;45:M270-277.
24. Alexander NB. Gait disorders in older adults. *J Am Geriatric Soc.* 1996:44:434-451.
25. Hageman P. Gait characteristics of healthy elderly: a literature review. *Issues on Aging.* 1995;18:1-9.
26. Perron M, Malouin F, Moffet H, McFadyen BJ. Three-dimensional gait analysis in women with total hip arthroplasty. *Clin Biomech.* 2000;15:504-515.
27. McGibbon CA, Krebs DE. Effects of age and functional limitation on leg joint power and work during stance phase. *J Rehabil Res Dev.* 1999;36:173-182.
28. Sliwinski MM, Sisto SA, Batavia M, Chen B, Forrest G. Dynamic stability during walking following unilateral total hip arthroplasty. *Gait Posture.* 2004;19:141-147.
29. McGibbon CA, Krebs DE, Puniello MS. Mechanical energy analysis identifies compensatory strategies in disabled elders' gait. *J Biomech.* 2001;34:481-490.