Available online at www.sciencedirect.com

ScienceDirect

Gait & Posture xxx (2007) xxx–xxx

GAIT & POSTURE

www.elsevier.com/locate/gaitpost

The effect of total knee replacement surgery on gait stability

David Mandeville, Louis R. Osternig, Li-Shan Chou [*]

Motion Analysis Laboratory, Department of Human Physiology, 1240 University of Oregon, Eugene, OR 97403, USA

Received 5 October 2006; received in revised form 21 February 2007; accepted 26 February 2007

Abstract

The purpose of this study was to investigate the effect of knee pain and total knee replacement (TKR) surgery on the gait stability of knee osteoarthritis (OA) patients compared to controls. Gait spatio-temporal measures, center of mass kinematics and pain levels of 21 TKR subjects and 21 controls (CON) were assessed during level walking and obstacle crossing at two testing periods, pre-surgery (P1) and 6 months post-surgery (P2). The TKR patients reported greater pain and disability than CONs at P1 and P2, walked and negotiated the obstacle more slowly and had a shorter stride length than CONs. After surgery, the TKR center of mass–center of pressure (COM–COP) separation distance and the peak anterior inclination angle were significantly smaller than CONs. Pain was found to be significantly related to sagittal plane measures, but not to similar measures in the frontal plane. The data suggest that total knee replacement surgery and pain affect gait stability predominantly in sagittal plane variables. The TKR subjects used a conservative strategy to manage the COM and COP in the sagittal plane, possibly to reduce the kinetic demands on the involved limb.

Keywords: Knee osteoarthritis; Total knee replacement; Gait analysis; Center of mass; Obstacle crossing

1. Introduction

Osteoarthritis is considered to be an independent risk factor for recurrent falls in community-dwelling mature fallers [1,2]. A deleterious relationship between knee osteoarthritis (OA) and standing balance has been reported indicating that knee OA patients have greater body sway during standing than controls [3–6]. This is thought to be the result of proprioceptive deficits, muscle weakness, and knee pain brought about by articular degeneration of the knee joint [5].

Several studies have suggested an association between knee pain and standing postural instability. For rheumatoid arthritis patients, Sherida et al. [7] reported a relationship between visual analog pain scores and lateral center of pressure (COP) velocity, possibly reflecting efforts to unload painful limbs. Hassan et al. [5] observed that knee pain and quadriceps strength were significant predictors of increased postural sway. Generalized musculoskeletal pain has also been found to be related to falls in older women [8]. Women who reported widespread pain had a 60% greater risk of falling, slower gait, and lower quadriceps strength when compared to women with no or mild pain. It was suggested that reflex muscle inhibition from chronic pain could compromise muscle responses to perturbation. It was suggested further that pain may decrease older adults' confidence in physical abilities, possibly mediating the relationship between pain and falls. Since OA patients have been shown to have both pain and static postural instability, it is plausible that they will also show gait instability. Further, if gait instability exists for end-stage knee OA subjects, it is possible that total knee replacement surgery will improve both knee pain and gait instability.

Total knee replacement (TKR) surgery is the treatment of choice for end-stage knee OA [9]. The goal of TKR is to relieve pain, correct deformity, and restore locomotor function [10]. While TKR has been shown to relieve pain [11], pain relief alone does not permit normal locomotion [12]. Some features of post-TKR gait alterations are reduced knee flexion during weight acceptance and altered stance-phase knee moment patterns [13]. However, the presence or

---

[*] Corresponding author. Tel.: +1 541 346 3391; fax: +1 541 346 2841.
E-mail address: chou@uoregon.edu (L.-S. Chou).

0966-6362/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2007.02.009

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

resolution of gait stability deficits for TKR patients requires further investigation.

It has been suggested that falls most commonly occur during activities of daily living (ADLs) [14], thus, evaluations of knee OA balance deficits should reflect the dynamic nature of these activities. Understanding the gait instability faced by knee OA and TKR patients may help to enhance the functional goals of rehabilitation. Therefore, the aim of this study was to assess the effect of knee pain and surgery on gait stability in TKR patients relative to controls during level and obstructed walking. Additionally, the relationship between knee pain/ADLs disability and gait stability was assessed. It was hypothesized that pre-surgical TKR candidates would show greater knee pain and gait instability than controls and that TKR values would resemble control levels post-surgically. It was also hypothesized that pain would be related to gait instability measures.

2. Method

Forty-three volunteers were recruited into two experimental groups: (1) total knee replacement (TKR, $n = 21$); (2) healthy age-matched control (CON, $n = 22$; Table 1). The study was approved by the Institutional Review Board and subject consent was obtained. TKR subjects displayed end-stage knee OA and were scheduled to receive a three-compartment posterior stabilized ($n = 18$) or a cruciate retaining ($n = 3$) prosthesis (Zimmer NexGen®, Warsaw, IN). The operations were performed by three orthopedic surgeons associated with the same group. Each patient received standard full-weight bearing rehabilitation protocols initiated the first day following surgery; however, no consistent regimen was followed by all TKR subjects. In order to assess the effect of knee pain and surgery on gait stability, TKR subjects underwent motion analysis testing at two time periods: within 2 weeks prior to surgery (P1) and 6 months post-surgery (P2). The 6-month post-surgical collection period was considered sufficient by attending physicians to allow healing of surgical trauma. Control subjects were tested at an initial collection period (P1), and at a second period 6 months later (P2). Exclusion criteria for all subjects included neurological or vestibular dysfunction, diabetes mellitus, Parkinson's disease, or a cerebrovascular accident.

Pain, stiffness, and ADL difficulty of all subjects were assessed via the Western Ontario and McMaster Universities Osteoarthritis Index, Visual Analog Scale (WOMAC/VAS) questionnaire. The questionnaire has been shown to be a reliable and valid multidimensional health status instrument [15].

For gait assessment, all subjects were fitted into a fall-arrest harness and instructed to walk along a 10 m walkway at their preferred speeds while barefoot. For obstacle crossing trials, subjects were instructed to walk along the walkway at their preferred speed while crossing a displaceable plastic tube obstacle placed in the walkway at 10% of body height. Several practice trials for each condition allowed subjects to become accustomed to experimental conditions. Up to five trials per subject were used for analysis, depending upon subject tolerance (mean = 3.7 trials).

Whole body motion data were collected using an eight-camera motion analysis system (Eagle Digital System, EVaRT 4.4, Motion Analysis Corp., Santa Rosa, CA), with a set of 33 reflective markers placed on bony landmarks of each subject [16]. Nineteen markers were used to define the foot, leg, and thigh segments of both lower extremities. These markers were placed between the 2nd and 3rd metatarsals (dorsal), and on the posterior calcaneus, medial and lateral malleoli, medial and lateral femoral epicondyles, lateral distal tibias and lateral distal thighs (wands), the sacrum, and both anterior superior iliac spines. Medial markers were removed following initial measurements. The two anterior superior iliac spine markers and one placed at the sacrum defined the pelvic segment. Fourteen additional markers defined the head, arm, forearm, and trunk segments (Fig. 1). Camera spatial arrangement was optimized to yield a capture volume with height = 3 m, length = 10 m, width = 1.5 m, and displacement accuracy ≤ 0.5 mm. Three-dimensional marker trajectory data were collected at 60 Hz and low-pass filtered using a recursive Butterworth filter (cutoff frequency = 8 Hz). Two force plates (AMTI, Newton, MA, model OR6-5-1) were used to obtain ground reaction data, sampled at 960 Hz and time-synchronized to the video sampling rate. The force plates, fixed to the foundation of the laboratory and mounted flush to the floor, were arranged in series, separated by 26 cm or positioned adjacent to each other, so that consecutive contralateral stance phases were collected.

External markers and estimated joint centers were used to calculate the three-dimensional locations of segmental COMs. Approximation of the segment mass and COM location were based on anthropometric data previously reported [17]. Whole body COM position data were calculated as the weighted sum of all 13 body segments, including head-neck, trunk, pelvis, two upper

Table 1
Mean anthropometric and WOMAC subscale values for TKR and CON groups across testing period (standard deviation)

	TKR		CON	
	P1	P2	P1	P2
Age (years)	63.7 (7.56)	64.0 (7.74)	62.7 (4.26)	63.1 (4.26)
Gender (women/men)	15/6	14/5	14/8	13/8
Height (m)	1.66 (0.09)	1.66 (0.09)	1.70 (0.09)	1.69 (0.05)
Weight (kg)	91.52† (17.83)	89.92† (18.65)	76.79 (12.46)	77.27 (12.83)
BMI (kg/m^2)	32.9† (4.95)	32.4† (5.36)	26.6 (3.35)	26.9 (3.3)
WOMAC pain (out of 100)	46.69† (22.32)	14.74*,† (15.12)	3.22 (2.75)	4.06 (3.76)
WOMAC ADLs (out of 100)	46.90† (23.42)	15.44*,† (12.14)	4.35 (3.85)	3.96 (3.57)

P1 and P2 are the periods.
† Indicates significant between-group difference ($P < .05$).
* Indicates significant within-group difference ($P < .05$).

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

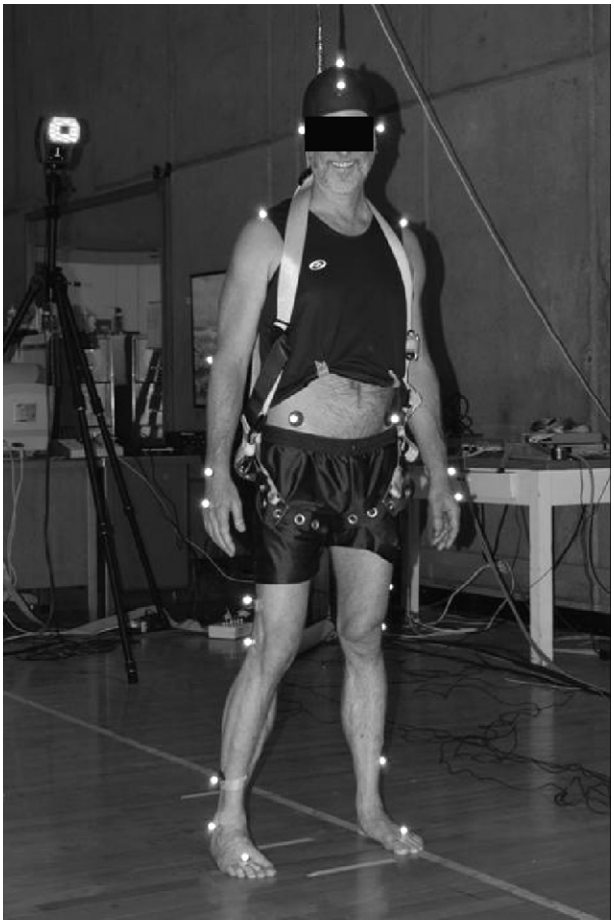
[redacted]

Fig. 1. Subject with marker set.

arms, two forearms (with hands), two thighs, two shanks, and two feet. Position derivatives of whole body COM were estimated with a generalized cross-validated spline algorithm [18]. Laboratory-written programs (Matlab v. 7.0 Mathworks Inc., Natick, MA, USA) were used to complete the data processing. The position of the COP under each foot was calculated using the reaction forces and moments recorded from the force plates. The angle formed between the vector connecting the COM and COP and the gravitational axis passing through the COP was determined in both the frontal and sagittal planes and denoted as anterior and medial COM–COP inclination angles, as previously described [19] (Fig. 2). Gait velocity, stride length, and COM–COP measures were analyzed for a gait cycle beginning and ending with foot strike of the involved limb for patients, and the dominant limb for controls. During obstacle crossing, the involved limb contacted the force plate preceding the obstacle.

The dependent variables measured at the two testing periods (P1 and P2) included: WOMAC/VAS pain and ADL disability scores, gait velocity (GV), stride length (SL), step width (SW), stride time (ST), maximum separation distance between the COM–COP in the anterior and medial directions (COM–COP$_A$; COM–COP$_M$; Fig. 2), and simultaneous anterior and medial velocities of the COM (AP$_v$; ML$_v$). Maximum anterior and medial COM–COP inclination angles were also calculated (θ_A; θ_M). Two-way mixed analyses of variance (ANOVAs) with factors of period and group, and repeated measures for period and trials were used to analyze between and within-group effects across time for each variable (SAS 9.1, Cary, NC, USA). Four simple effects were explored for each condition: within-group differences for CON and TKR at P1 and P2, and between-group differences at P1 and P2. A Bonferroni correction was used to adjust the alpha level to .0125. An independent samples t-test (α = .05) was used to assess between-group differences for WOMAC/VAS scores. A dependent samples t-test (α = .05) was used to assess within-group differences for WOMAC/VAS scores. The relationships between the WOMAC subscales to the COM–COP interaction variables were assessed via Pearson correlation coefficients (α = .05) computed at P1 and P2. By using a moderate effect size, the minimum number of subjects in each group was determined to be 20 (.05 alpha; .1 beta).

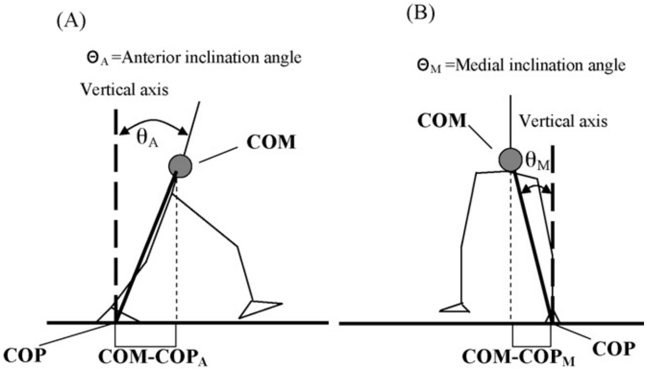

Fig. 2. Inclination angle and COM–COP separation distance in sagittal (A) and frontal (B) planes.

3. Results

Pre-surgically, four TKR subjects were not able to complete obstacle crossing due to pain, and two TKR subjects and one control subject were lost to attrition at P2. Following surgery, all remaining TKR subjects (n = 19) successfully completed the obstacle crossing condition. No within-group differences for anthropometric values were seen across testing periods for either group (Table 1). However, at both testing periods, the TKR group was significantly heavier than CON (P = .012), which was reflected in significantly greater BMI values (P = .0001).

3.1. WOMAC/VAS variables

At P1, the TKR group reported significantly greater pain (P < .0001) and ADLs disability than controls (P < .0001, Table 1). Although these variables improved significantly for the TKR subjects across testing periods, they remained significantly greater than CON at P2 (P = .002 and P = .001, respectively).

3.2. Gait spatio-temporal measures

For level walking at P1, the TKR group walked with significantly slower walking velocity (P = .0003) and

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

Table 2
Mean spatio-temporal values during level walking and obstacle crossing for TKR and CON groups across testing periods (standard deviation)

Condition	TKR level		CON level		TKR obstacle		CON obstacle	
	P1	P2	P1	P2	P1	P2	P1	P2
Gait velocity (m/s)	0.94† (0.38)	1.06*,† (0.32)	1.14 (0.37)	1.21 (0.3)	0.73† (0.45)	0.82† (0.37)	0.94 (0.41)	0.99 (0.36)
Stride length (cm)	109.6† (28.8)	117.1*,† (24.2)	125.4 (28.3)	129.1 (23.1)	115.5† (38.8)	118.5 (56.6)	129.9 (35.7)	130.1 (53.7)
Step width (cm)	11.1 (4.8)	9.6* (4.2)	11.1 (4.8)	9.4* (4.0)	11.2 (7.2)	9.4 (6.0)	11.0 (6.4)	9.6 (6.0)
Stride time (s)	1.20 (0.28)	1.12* (0.18)	1.11 (0.28)	1.08 (0.17)	1.64† (0.58)	1.47 (0.67)	1.40 (0.53)	1.34 (0.64)

P1 and P2 are the periods.

† Significantly different between groups, within period ($P < .0125$).

* Significantly different between testing periods ($P < .0125$).

shorter stride length ($P = .0002$) than CONs (Table 2). Post-surgically, the TKR group significantly increased walking velocity ($P = .0005$) and stride length ($P = .0044$), and significantly decreased step width ($P = .0021$) and stride time ($P = .0019$). However, post-surgical TKR velocity remained significantly slower and stride length significantly shorter than CONs ($P = .001$, $P = .0005$, respectively). Across testing periods, the CONs significantly decreased their step width ($P = .0012$). For obstacle crossing at P1, the TKR group had significantly slower gait velocity ($P = .0009$), shorter stride length ($P = .007$) and increased stride time than CONs ($P = .0029$). At P2, TKR obstacle crossing velocity remained significantly slower than CONs ($P = .0014$). No significant within-group differences were seen for either group across testing periods for obstacle crossing.

3.3. COM–COP measures

For level walking, the TKR subjects walked with a significantly smaller COM–COP$_A$ at both P1 ($P = .0064$) and P2 ($P < .0001$, Fig. 3A). The AP$_v$ was significantly slower for TKR compared to CONs at P1 ($P = .0001$, Fig. 3B). Although TKR COM velocity was significantly increased at P2 ($P = .0008$), it remained significantly less than CONs ($P = .0005$). TKR level walking θ_A values were significantly less than CONs at both P1 ($P = .0055$) and P2 ($P < .0001$, Fig. 3C). The TKR group crossed the obstacle with a significantly smaller COM–COP$_A$ at P2 compared to CONs ($P = .0007$). TKR AP$_v$ values approached significance at P2 ($P = .0182$) for obstacle crossing, while θ_A values were significantly less than CONs at P2 ($P = .0004$). No significant between or within-group differences were

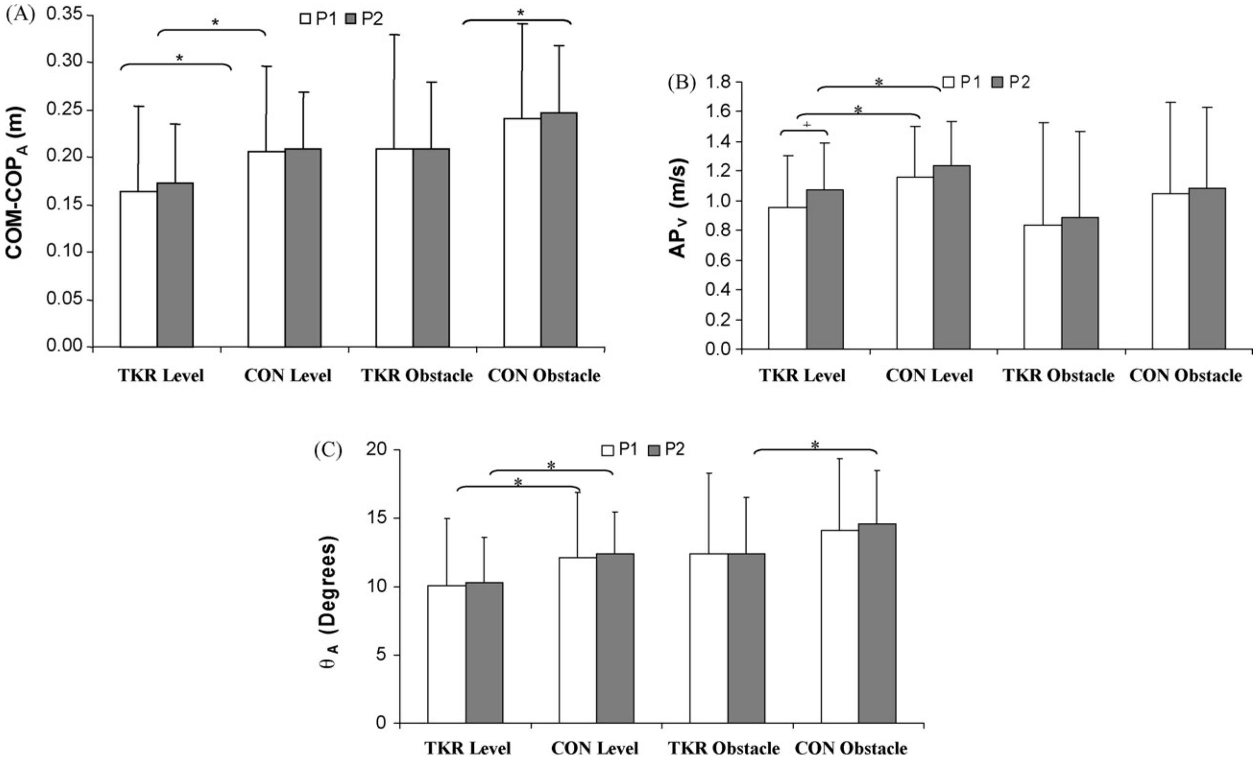

Fig. 3. Means and standard deviations for TKR and CON during level and obstructed walking: (A) maximum anterior COM–COP separation; (B) instantaneous COM anterior velocity at maximum COM–COP separation; (C) maximum anterior COM-COP inclination angle. *Significant between-group difference, $^{+}$significant within-group difference.

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

Table 3
Mean maximal medial COM–COP separation, concurrent medial velocity of the COM, and maximal medial inclination angle during level walking and obstacle crossing for TKR and CON across testing period (standard deviation)

Group/condition	TKR level		CON level		TKR obstacle		CON obstacle	
	P1	P2	P1	P2	P1	P2	P1	P2
COM–COP$_M$ (m)	0.086 (0.037)	0.077 (0.026)	0.084 (0.036)	0.074 (0.025)	0.080 (0.048)	0.075 (0.035)	0.082 (0.043)	0.071 (0.032)
ML$_v$ (m/s)	0.06 (0.09)	0.05 (0.06)	0.07 (0.07)	0.06 (0.05)	0.09 (1.1)	0.09 (0.08)	0.11 (0.09)	0.09 (0.07)
θ_M (°)	5.13 (2.18)	4.64 (1.48)	4.98 (2.08)	4.42 (1.39)	4.81 (2.87)	4.47 (2.08)	4.86 (2.47)	4.23 (1.88)

P1 and P2 are the testing periods.

found for the frontal plane COM–COP measures for both level and obstructed walking (Table 3).

3.4. Relationships between pain and gait stability measures

At P1, significant but moderate correlation coefficients were found between the WOMAC/VAS pain and ADLs and several gait variables for level walking (Table 4). The correlations remained significant for level walking at P2, but were somewhat smaller than at P1. A similar pattern of relationships, but of lesser magnitude, was observed for obstacle crossing at P1 and P2. No significant relationships were found between the WOMAC/VAS scores and frontal plane COM–COP variables for either level walking or obstacle crossing at P1 or P2.

4. Discussion

Pain secondary to degenerative knee OA has been shown to adversely affect static postural control [5], thus, it is plausible that pain may likewise influence gait stability. TKR subjects were found to walk with a conservative management of the COM motion in the sagittal plane prior to and following surgery in response to knee pain and to avoid imbalance. However, the knee joint pain measured pre-surgically did not compromise the ability of knee OA subjects to maintain frontal plane gait stability.

The 6-month post-surgery improvements of the WOMAC scores support previously reported effectiveness of TKR surgery in improving the quality of life of end-stage knee OA patients [11]. The TKR group improvement in WOMAC scores at P2 was accompanied by changes in spatio-temporal gait variables that moved closer to, but remained significantly different from CONs. The TKR pain score remained significantly greater than CON at P2 and likely underscored the continued abatement of their post-surgical level walking and obstacle crossing velocity. For both conditions, TKR subjects showed a shorter stride length, and thus a shorter base of support (BOS) than CON, which possibly represented an effort to minimize pain and to reduce the kinetic demands placed on the involved limb. While improvement of the TKR level walking spatio-temporal variables may indicate enhanced locomotor ability following surgery, 6 months may be insufficient post-surgical recovery time to allow for resolution of symptoms and attainment of control gait velocity values [13].

Table 4
Pearson correlation coefficients (r) between WOMAC pain/ADLs scores and maximal anterior COM–COP separation, concurrent velocity of the COM and maximal anterior inclination angle for combined groups at P1 and P2

	P1		P2	
	Pain	ADLs	Pain	ADLs
COM–COP$_A$	$-.433^*$	$-.456^*$	$-.296$	$-.339^*$
AP$_v$	$-.486^*$	$-.537^*$	$-.294$	$-.390^*$
θ_A	$-.437^*$	$-.463^*$	$-.258$	$-.317^*$

* Significant at $P < .05$.

During level and obstructed walking, frontal plane COM–COP measures have been used as functional indicators that may distinguish imbalanced patients from healthy controls [20–22]. The results of this study indicate that, prior to and following surgery, TKRs and CONs walked and crossed over an obstacle similarly, suggesting that TKR subjects have the ability to appropriately manage the COM within the BOS during locomotion. All subjects maintained frontal plane COM–COP values within the ranges reported previously for healthy subjects of comparable age [16,19,23].

Standing postural sway [6] and lateral COP velocity [7] have previously been shown to increase in response to pain for knee OA subjects. However, the conditions of the static testing paradigm preclude a stepping response. In contrast, the balance control strategy of locomotion utilizes a stepping response (transient BOS) allowing for potential COM excursions beyond the BOS and greater planar velocities of the COM. Therefore, during gait testing in the current study, the TKR subjects may have been allowed more freedom to alter their BOS in response to knee pain. While the TKR subjects showed a similar frontal plane BOS compared to CONs, they showed a differential control of the stepping response in the sagittal plane.

Across testing periods, the TKRs ambulated with a persistent conservative management of the COM within the BOS in the plane of progression as indicated by less maximum anterior COM–COP inclination angles than CONs. The diminished TKR group maximum anterior COM–COP separation and concurrently slower anterior velocity of the COM, compared to CONs, provide further evidence of conservative efforts to maintain the COM

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

anterior velocity and BOS within an adjusted ‘‘feasible range,’’ as suggested by Pai and Patton [24]. During walking, greater anterior COM–COP separation during single limb support would result in larger external flexion moments about the lower extremity joints, thus increasing the demand for resistive muscular force generation. Further analyses of the TKR subjects in this study revealed less knee flexion and concomitantly diminished knee extensor moments during mid-stance when compared to CON prior to and following surgery [25]. Thus, the presence of the conservative TKR sagittal BOS appears in conjunction with residual restricted knee flexion and decreased knee extensor activation during weight acceptance. These results support the conclusion by Hahn and Chou [16] that diminished anterior/posterior COM–COP measures indicate a conservative strategy for reduction of the kinetic demands of the supporting limb.

The WOMAC pain scores did not relate significantly to the frontal plane COM–COP measures, suggesting that knee pain did not adversely affect the hip abductor musculature which helps to control frontal plane trunk sway [26], but may have inhibited the knee extensor musculature responsible for sagittal plane control of the stance limb. The negative relationship between pain scores and the anterior COM–COP variables ($r = -.433$ to $-.486$) was possibly mediated via the diminished knee extensor moment, as pain has previously been reported to negatively influence the knee extensors [5]. This suggests that the TKR subjects adjusted their gait due to knee pain in the plane of progression in order to reduce forces to the pathologic knee joint.

The difference in BMI between TKR and control subjects is a limitation of this study. It is possible that soft tissue composition could have affected the COM calculation. It has been shown previously that BMI was a weak but statistically significant predictor of COP excursion while standing ($r^2 = 2.53\%$) [27]. However, DeVita and Hortobagyi [28] reported that healthy obese and lean adults (mean BMI = 42.3 kg/m^2 versus 22.7 kg/m^2) had identical knee torques and powers when walking at the same speed. In current study, the between-group discrepancy is consistent with BMIs found in TKR patients and the otherwise healthy age-matched population. The mean pre–post surgery TKR BMI of ~32.7 kg/m^2 reflects typical values for patients undergoing this procedure [29] while the mean control BMI of ~26.7 kg/m^2 approximates the norm for individuals 60–74 years of age [30].

In conclusion, the effects of pain and TKR on gait stability are most notable in sagittal plane variables. Similarly, the clinical scores for pain and ADLs disability were related to these variables. This is reflected in the conservative sagittal plane control of the COM and COP demonstrated by the TKR group pre and post-surgery. Since the TKR group reported significant knee pain before and 6-month post-surgery it is possible that a conservative strategy was needed to attenuate the kinetic demands to the knee, which were more pronounced in sagittal compared to frontal plane balance control.

Acknowledgements

The authors thank Brick A. Lantz, M.D., Craig G. Mohler, M.D., Brian A. Jewett, M.D., and Crystal L. Mills from Orthopedic Healthcare Northwest, P.C., Eugene, OR, and Robin High, Ph.D., Susan Ewers C.P.O., and Yuki Inaba from the University of Oregon for their contributions to this study.

References

[1] Nevitt MC, Cummings SR, Kidd S, Black D. Risk factors for recurrent nonsyncopal falls. J Am Med Assoc 1989;261(18):2663–8.

[2] Jones G, Nguyen T, Sambrook PN, Lord SR, Kelly PJ, Eisman JA. Osteoarthritis, bone density, postural stability, and osteoporotic fractures: a population based study. J Rheumatol 1995;22:921–5.

[3] Hurley MV, Scott DL, Rees J, Newham DJ. Sensorimotor changes and functional performance in patients with knee osteoarthritis. Ann Rheum Dis 1997;56:641–8.

[4] Wegener L, Kisner C, Nichols D. Static and dynamic balance responses in persons with bilateral knee osteoarthritis. J Ortho Sports Phys Ther 1997;25(1):13–8.

[5] Hassan BS, Mockett S, Doherty M. Static postural sway, proprioception, and maximal voluntary quadriceps contraction in patients with knee osteoarthritis and normal control subjects. Ann Rheum Dis 2001;60:612–8.

[6] Hinman RS, Bennell KL, Metcalf BR, Crossley KM. Balance impairments in individuals with symptomatic knee osteoarthritis: a comparison with matched controls using clinical tests. Rheumatology 2002;41:1388–94.

[7] Sherida SK, Hen TA, Geurts AC, Bosch PP, Laan RF, Mulder T. Postural control in rheumatoid arthritis patients scheduled for total knee arthroplasty. Arch Phys Med Rehabil 2000;81:1489–93.

[8] Leveille SG, Bean J, Bandeen-Roche K, Jones R, Hochberg M, Guralnik JM. Musculoskeletal pain and risk for falls in older disabled women living in the community. J Am Geriatr Soc 2002;50:671–8.

[9] Felson D, Lawrence RC, Dieppe PA, Hirsch CG, Helmick CG. Osteoarthritis: new insights. Part 1: the disease and its risk factors.. Ann Intern Med 2000;133(8):635–46.

[10] Collopy MC, Murry M, Gardner GM, DiUlio RA, Gore DR. Kinesiologic measurements of functional performance before and after geometric total knee replacement: one year follow up of twenty cases. Clin Orthop 1977;126:196–202.

[11] Bachmeier CJ, March LM, Cross MJ, Lapsley HM, Tribe KL, Courtenay BG, et al. A comparison of outcomes in osteoarthritis patients undergoing total hip and knee replacement surgery. Osteoarthritis Cartilage 2001;9(2):137–46.

[12] Skinner HB. Pathokinesiology and total joint arthroplasty. Clin Orthop 1993;288:78–86.

[13] Andriacchi TP. Evaluation of surgical procedures and/or joint implants with gait analysis. Instr Course Lect 1990;39:343–50.

[14] Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. N Engl J Med 1998;319: 1701–7.

[15] Bellamy N, Buchanan W, Boldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. J Rheumatol 1988;15(12):1833–40.

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009

[16] Hahn ME, Chou LS. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. J Biomech 2004;37:837–44.

[17] Winter DA. Biomechanics and motor control of human movement. New York: John Wiley & Sons; 1990.

[18] Woltring HJ. A FORTRAN package for generalized, cross-validatory spline smoothing and differentiation. Adv Eng Software 1986;8: 104–7.

[19] Lee HJ, Chou LS. Detection of gait instability using the center of mass and center of pressure inclination angles. Arch Phys Med Rehabil 2006;87:569–75.

[20] Chou LS, Kaufman KR, Hahn ME, Brey RH. Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. Gait Posture 2003;18:125–33.

[21] Hahn ME, Chou LS. Can motion of individual body segments identify dynamic instability in the elderly? Clin Biomech 2003;18: 737–44.

[22] Hahn ME, Farley AM, Lin V, Chou LS. Neural network estimation of balance control during locomotion. J Biomech 2005;38:717–23.

[23] Chou LS, Kaufman KR, Brey R, Daganich LF. Motion of the whole body's center of mass when stepping over obstacles of different heights. Gait Posture 2001;13:17–26.

[24] Pai Y-C, Patton J. Center of mass velocity-position prediction for balance control. J Biomech 1997;30:347–54.

[25] Mandeville DS, Osternig LR, Chou LS. The effect of total knee replacement on dynamic support of the body. In: Davis I, Hamill J, Piazz S, editors. Proceedings of the 30th Annual Meeting of the American Society of Biomechanics, 2006 (Abstract).

[26] MacKinnon CD, Winter D. Control of whole body balance in the frontal plane during human walking. J Biomech 1993;26:633–44.

[27] Jadelis K, Miller ME, Ettinger WH, Messier SP. Strength, balance and the modifying effects of obesity and knee pain: results from the Observational Arthritis Study in Seniors (OASIS). J Am Geriatr Soc 2001;49:884–91.

[28] DeVita P, Hortobagyi T. Obesity is not associated with increased knee joint torque and power during level walking. J Biomech 2003;36: 1355–62.

[29] Namba RS, Paxton L, Fithian DC, Stone ML. Obesity and perioperative morbidity in total hip and total knee arthroplasty patients. J Arthroplasty 2005;20(7 Suppl. 3):46–50.

[30] Ogden CL, Fryar CD, Carroll MD, Flegal KM. Mean body weight, height, and body mass index, United States 1960–2002. Adv Data 2004;347:1–17.

Please cite this article in press as: Mandeville D, et al., The effect of total knee replacement surgery on gait stability, Gait Posture (2007), doi:10.1016/j.gaitpost.2007.02.009