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A multiple regression normalization approach to evaluation of gait in total knee arthroplasty patients

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ABSTRACT

Background: Gait features characteristic of a cohort may be difficult to evaluate due to differences in subjects' demographic factors and walking speed. The aim of this study was to employ a multiple regression normalization method that accounts for subject age, height, body mass, gender, and self-selected walking speed in the evaluation of gait in unilateral total knee arthroplasty patients.
Methods: Three-dimensional gait analysis was performed on 45 total knee arthroplasty patients and 31 aged-matched controls walking at their self-selected speed. Gait data peaks including joint angles, ground reaction forces, net joint moments, and net joint powers were normalized using subject body mass, standard dimensionless equations, and a multiple regression approach that modeled subject age, height, body mass, gender, and self-selected walking speed.
Findings: Normalizing gait data using subject body mass, dimensionless equations, and multiple regression approach resulted in a significantly lower knee adduction moment and knee extensor power in total knee arthroplasty patients compared to controls ($p < 0.05$). In contrast to normalization using body mass and dimensionless equations, multiple regression normalization greatly reduced variance in gait data by minimizing correlations with subject demographic factors and walking speed, resulting in significantly higher peak hip extension angles and peak hip flexion powers in total knee arthroplasty patients ($p < 0.05$).
Interpretation: Total knee arthroplasty patients generate greater hip extension angles and hip flexor power and have a lower knee adduction moment than healthy controls. This gait pattern may be a strategy to reduce muscle and joint loading at the knee.

1. Introduction

Total knee arthroplasty (TKA) is the established treatment for end-stage knee osteoarthritis when conservative treatment options have been exhausted. In 2005, approximately 500,000 TKA procedures were performed in the United States alone at a cost exceeding $11 billion (Losina et al., 2009). It is estimated that close to 3.48 million TKAs will be performed annually by 2030 (Kurtz et al., 2007). While TKA has been shown to reduce pain, improve knee function, and increase quality of life (Ethgen et al., 2004; Hatfield et al., 2011), TKA patients are known to exhibit post-operative compensatory gait patterns to minimize joint loading and pain at the affected knee. This includes walking with less knee flexion (Mandeville et al., 2007; McClelland et al., 2011), a lower knee adduction moment (Alnahdi et al., 2011; McClelland et al., 2010), and a shorter swing phase in the affected leg (Andriacchi et al., 1982). In addition, lower ankle plantar–flexor power and higher hip flexor power has been observed in TKA subjects compared to aged-matched controls (Levinger et al., 2013).

Gait characteristics of an individual, including kinematics and net joint moments, are influenced by age, height, body mass, and gender (Moisio et al., 2003; Senden et al., 2012), as well as by variations in self-selected walking speed (Andriacchi et al., 1977; Lelas et al., 2003), including fluctuations within a single testing session (Benedetti et al., 2013; Yogev-Seligmann et al., 2008). Ultimately, variability in subject demographic factors increases dispersion of gait data and may limit capacity to discern some pathological movement patterns (Boyer et al., 2008; Hof, 1996). The dimensionless normalization (DS) equations of Hof (1996) are widely used in clinical gait analysis to normalize gait data to subject height and weight, and assume proportional scaling (Pierrynowski and Galea, 2001); however, the use of DS in normalizing spatiotemporal data, ground reaction forces (GRFs), and net joint moments has been shown to result in residual correlations between the normalized gait data and subject walking speed (Carty and Bennett,

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Table 1
Demographic data for TKA patients and controls.

Demographics	TKA patients (n = 45)			Controls (n = 31)			P value
	Mean	SD	Range	Mean	SD	Range	
Walking speed (m/s)	1.3	0.2	1.0–1.7	1.3	0.1	1.0–1.6	0.284
Age (years)	69.5	8.4	53.0–87.0	69.9	8.0	55.0–88.0	0.826
Height (m)	1.7	0.1	1.5–1.9	1.6	0.1	1.5–1.8	0.110
Body mass (kg)	86.6	17.4	58.6–127.4	75.0	13.4	51.4–99.8	0.003
BMI (kg/m^2)	30.5	4.9	23.3–43.1	27.7	3.8	20.6–33.8	0.008
Gender*	Male: 26, Female: 19			Male: 12, Female: 19			0.102

Symbol definitions are as follows: SD, standard deviation; BMI, body mass index.
* Chi-square test was employed.

2009; Lelas et al., 2003), body mass (Wannop et al., 2012), and gender (Boyer et al., 2008; Cho et al., 2004).

Statistical techniques, including use of linear (Lelas et al., 2003; O'Malley, 1996), multiple-linear (Lee et al., 1999; Macellari et al., 1999; Senden et al., 2012), and non-linear (Wannop et al., 2012) regression models, have been employed to scale gait data to subject anthropometry; however, these models do not account for variations in subject height, body mass, age, and gender and are rarely used to account for variations in subject walking speed. To minimize the influence of self-selected walking speed variations on gait data, subjects are often 'speed-matched' between groups, which can be difficult and time consuming to carry out in practice. Multiple-regression approaches to data normalization have been used to predict spatiotemporal gait data from anthropometrics and walking speed (Dixon et al., 2014); however, these approaches have received little attention to date and have not been used in models of joint angles, joint moments, and joint powers.

The aim of this study was twofold. First, to employ a multiple regression normalization (MR) method to minimize variation in subject joint angles, GRFs, net joint moments, and joint powers due to walking speed, body height, body mass, age, and gender in healthy adults; and second, to use this normalization approach to compare joint angles, GRFs, net joint moments, and net joint powers between TKA patients and healthy adults. We hypothesized that MR would reveal significant joint-level differences in angles, net moments, and powers in TKA patients and controls by eliminating effects of subject anthropometry and walking speed variations.

2. Methods

2.1. Experimental protocol

Gait data for 45 TKA patients and 31 aged-matched healthy controls were selected retrospectively from a gait database (Table 1). All TKA patients underwent unilateral arthroplasty by an experienced knee surgeon between August 2004 and July 2006 and received a posterior stabilized total knee replacement (Genesis-II PS, Smith and Nephew, Memphis, Tennessee, USA). Eighteen patients had joint replacement surgery on their left knee, while 27 had this surgery on their right knee. TKA patients were excluded if they had previous history of neurological or visual impairments, other orthopedic procedures involving the lower extremities, or were unable to ambulate without a gait aid. Gait data were collected between 12 and 18 months post-operatively from the affected limb of TKA patients. Control subjects who had no history of lower limb impairment or previous surgery were recruited through advertisements at a local clinic. Data for control subjects were collected and analyzed using the same proportion of left and right knees as the TKA group. Ethics approval was granted from the relevant Human Research Ethics Committees, and written informed consent was provided according to the Committees' guidelines.

Three-dimensional gait data were acquired during a single testing session in a gait laboratory. Retro-reflective markers were placed on each subject bilaterally using a modified Helen Hayes marker set (Kadaba et al., 1990). Joint kinematics was measured using an 8-camera Vicon Motion Analysis System (Vicon, Oxford Metrics, Oxford, UK), while GRFs were recorded simultaneously using two instrumented force platforms (Kistler, Switzerland, and AMTI, Watertown, MA, USA). Video and analog force-plate data were sampled at 100 Hz and 1000 Hz, respectively. Marker data were filtered with a low-pass, fourth-order Butterworth filter with a cut-off frequency of 4 Hz.

Joint kinematics was calculated using inverse kinematics and net joint moments and powers were calculated from inverse dynamics. Calculations were performed using custom scripts written in Vicon Bodybuilder (Vicon, Oxford Metrics, Oxford, UK), as described previously (Schache and Baker, 2007). Peaks of joint angle, net joint moment, and net joint power curves at the hip, knee, and ankle joints were evaluated, as well as peaks of the vertical GRF (two peaks, occurring at early and late stance, and one trough at mid stance), fore–aft GRF (two peaks, occurring in early and late stance), and medial–lateral GRF (one peak at early stance) (Fig. 1). Foot progression angle, defined as the angle between the direction of progression of the subject and midline of the foot, was computed by averaging the progression angles between 15% and 50% of stance phase (foot flat) (Simic et al., 2013).

2.2. Data normalization

Peak GRFs, net joint moments, and net joint powers at the hip, knee, and ankle were normalized to subject height and body mass using non-dimensional equations reported previously (Hof, 1996):

$$F_n = \frac{F_r}{m_0 g}, \quad (1)$$

$$M_n = \frac{M_r}{m_0 g l_0}, \quad (2)$$

$$P_n = \frac{P_r}{m_0 g^{\frac{3}{2}} l_0^{\frac{1}{2}}}, \quad (3)$$

where, F_r and F_n represent the raw and normalized peak GRFs (vertical, fore–aft, and medial–lateral), respectively; M_r and M_n represent the raw and normalized peak net joint moments at the hip, knee, and ankle in the sagittal, coronal, and transverse plane, respectively; P_r and P_n represent the raw and normalized peak net joint powers at the hip, knee, and ankle in the sagittal plane, respectively; l_0 is the subject body height, and g is the universal gravitational acceleration constant. Gait data were normalized using Eqs. (1)–(3) in both the TKA patients and controls. Normalization of joint angles was not performed using DS, since joint angle data are dimensionless (Hof, 1996). The peaks of net joint moments and net joint powers were also normalized by division of subject body mass.

Peaks of these gait data were also normalized using a MR approach which calculates the ratio of the original gait data and fitted values from a regression model developed using the control cohort data as follows:

$$y_i = \beta_0 + \sum_{j=1}^{p} \beta_j x_{i,j} + \epsilon_i \quad (4)$$

where y_i represents the dependent variable including peaks of joint angles, net joint moments, and net joint powers at the hip, knee, and ankle in the sagittal, coronal, and transverse plane, and GRFs for the i-th observation; $x_{i,j}$ represents the j-th independent variables including walking speed, age, height, body mass, and gender for the i-th observation; β_0 represents the linear regression line intercept term; β_j represents the coefficient for the j-th independent variables; and $\epsilon_i \sim N(0, \sigma^2)$