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Short communication

Normalization of joint moments during gait: a comparison of two techniques

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Abstract

Joint moments are commonly used to characterize gait. Factors like height and weight influence these moments. This study determined which of two commonly used normalization methods, body mass or body weight times height, most reduced the effects of height and weight on peak hip, knee, and ankle external moments during walking. The effectiveness of each normalization method in reducing gender differences was then tested. Gait data from 158 normal subjects were analyzed using unnormalized values, body mass normalized values, and body weight times height normalized values. Without normalization, height or weight accounted for 7–82% of the variance in all 10 peak components of the moments. With normalization, height and weight accounted for at most 6% of the variance with the exception of the hip adduction moment normalized by body weight times height and the ankle dorsiflexion moment normalized by body mass. For the hip adduction moment normalized by body weight times height, height still accounted for 13% of the variance ($p<0.001$) and for the ankle dorsiflexion moment normalized by body mass, 22% of the variance ($p<0.001$). After normalization, significant differences between males and females remained for only two out of 10 moments with the body weight times height method compared to six out of 10 moments with the body mass method. When compared to the unnormalized data, both normalization methods were highly effective in reducing height and weight differences. Even for the two cases where one normalization method was less effective than the other (hip adduction-body weight times height; ankle dorsiflexion-body mass) the normalization process reduced the variance ascribed to height or weight by 48% and 63%, respectively, as compared to the unnormalized data.

Keywords: Gait; Normalization; Kinetics; Biomechanics; Anthropometrics

1. Introduction

Joint moments obtained from gait analysis are commonly used to characterize normal and pathologic gait and to make comparisons within and between populations. Most often, it is of interest to eliminate the variation that exists due to height and weight so that differences due to walking mechanics can be revealed. Two common approaches for normalization of joint moments include dividing the joint moment by body mass (N m/kg) (Winter, 1991) or dividing the joint moment by body weight times height (unitless or % body weight times height) (Andriacchi and Strickland, 1985). Previous authors (Andriacchi and Strickland, 1985; O'Malley, 1996; Hof, 1996; Sum, 1998; Pierrynowski and Galea, 2001) have investigated either a single normalization technique or various aspects of the normalization process; however a comprehensive analysis comparing the effectiveness of these normalization methods in a large group of adult subjects has not been done. Therefore, there is little evidence to support which normalization method is the most effective at reducing variation due to height and weight.

The aim of this project was to determine which of these two commonly used normalization methods, body mass or body weight times height, most reduced the

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effects of height and weight on peak hip, knee, and ankle external moments during walking in a group of normal subjects. In addition, the effectiveness of each normalization method in reducing gender effects, which may occur secondarily from height and weight differences between males and females, was tested.

2. Materials and methods

Data from 172 normal subjects who were tested in the gait laboratory between February 1991 and November of 1999 were examined. To be included in the study all subjects had to be free of lower extremity pathology and have a right and left side walking trial between 0.9 and 1.4 m/s. Walking speed was used as an inclusion criterion to minimize the effects of walking speed on the moments. From the original group of 172, a group of 158 subjects (74 females, 84 males) met the inclusion criteria (Table 1). The 14 subjects that were excluded had right or left side walking trials outside the range of 0.9–1.4 m/s. Internal Review Board approval was granted and informed consent was obtained from all subjects.

Three-dimensional kinematics and ground reaction forces were collected using an optoelectronic camera system with passive markers (CFTC, Chicago, IL) and a multicomponent force plate (Bertec, Columbus, OH). Inverse dynamics were used to calculate the external moments at the hip, knee and ankle joint centers. The external moment includes the moment about the joint center created by the ground reaction force and inertial forces. An external moment is equal and opposite to an internal moment that is created by muscles, soft tissues and joint contact forces. Full details have been previously described (Hurwitz et al., 1998; Andriacchi et al., 1997). Subjects were instructed to walk at self-selected speeds of normal, slow, and fast with multiple trials collected at each speed. A representative trial around 1.2 m/s was chosen for all subjects. The average speed for representative walking trials was 1.18 ± 0.1 m/s (0.9–1.4 m/s) and was not significantly different between males and females ($p = 0.804$).

A forward stepwise multiple regression model ($p_{in} = 0.5$, $p_{out} = 0.1$) was used to determine how much of the variance in each specified moment was attributed to height, weight, and speed. The peak external joint moments included in the analysis were hip flexion, extension, abduction, adduction, internal rotation, and external rotation; knee flexion, extension, and adduction; and ankle dorsiflexion. The regression model was run on three data sets, the unnormalized moments, moments normalized by body mass, and moments normalized by body weight times height. The primary endpoint in the regression models was the adjusted r^2 attributable to height, weight, or speed with the effectiveness of the normalization being evaluated by how much this value was reduced. Speed was included in the analysis to monitor any remaining effect it had on the moments. Statistical analyses evaluating the variance, skewness, and kurtosis demonstrated that all three data sets had normal distributions (p values from one-sample Kolmogorov–Smirnov tests from unnormalized data ranged from 0.06 to 0.46 and normalized data from 0.21 to 0.99). Plots of residuals vs. height and weight were also analyzed, demonstrating that the normalization process resulted in homoscedasticity. To determine the separate effects of height, weight, and speed on the moments, univariate Pearson correlations were also calculated. In order to determine whether the normalization schemes reduced differences due to gender, t-tests were performed. Comparable results were obtained for right and left sides from all analyses so results are reported for the right side only. A significance level of $\alpha < 0.05$ was used for all analyses.

Table 1
Demographics for males and females. Mean ± standard deviation

	Males ($n = 84$)	Females ($n = 74$)	p-value
Age (yr)	31 ± 12	36 ± 15	0.025
Mass (kg)	80.9 ± 13.2	64.8 ± 12.3	<0.001
Height (m)	1.79 ± 0.07	1.66 ± 0.07	<0.001

3. Results

Without normalization, height or weight had significant effects on the variance in all 10 moments accounting for between 7% and 82% of the variance (Table 2). With the body weight times height and body mass normalization methods, height and weight accounted for 6% or less of the variance in eight out of 10 moments. For two moments, hip adduction and ankle dorsiflexion, height accounted for greater than 10% of the variance. Specifically, with the body mass normalized method, height still explained 13% of the variance in the hip adduction moment ($p < 0.001$) while with the body mass method, height still accounted for 22% of the variance in the ankle dorsiflexion moment ($p < 0.001$). Regardless of the data set, speed accounted for between 2% and 18% of the variance.

The univariate analyses indicated that weight and height both had significant correlations with the moments (Table 3). Since weight was usually more highly correlated with the moment than height, weight entered the multiple regression analyses first for the unnormalized data. As expected, height and weight were correlated ($r = 0.603$, $p = <0.001$) so that often times once weight was accounted for in the multiple regression analysis, height no longer had a significant effect.

Table 2
Results from the forward stepwise regression model for the unnormalized, body mass, and body weight times height normalized data sets. The adjusted r^2 represents the proportion of variance of the moment explained by height, weight, or speed. For example, for the unnormalized hip flexion moment, weight entered the equation first explaining 35% of the variance in this moment (adj $r^2 = 0.35$) followed by speed, which explained an additional 11% of the variance (Δadj $r^2 = 0.11$). Therefore, together these two variables accounted for 46% of the variance in the hip flexion moment (adj $r^2 = 0.46$)

Peak joint moment	Unnormalized data				Body mass normalized data				Body weight times height normalized data			
	Variable in	adj r^2	Δadj r^2	p-value	Variable in	adj r^2	Δadj r^2	p-value	Variable in	adj r^2	Δadj r^2	p-value
Hip flexion	Wt.	0.35	0.35	<0.001	Speed	0.18	0.18	<0.001	Speed	0.18	0.18	<0.001
	Speed	0.46	0.11	<0.001								
Hip extension	Wt.	0.18	0.18	<0.001	Speed	0.10	0.10	<0.001	Speed	0.10	0.10	<0.001
	Speed	0.25	0.07	<0.001	Wt. (–)	0.12	0.02	0.041	Wt. (–)	0.16	0.06	0.001
	Ht.	0.28	0.03	0.011	Ht.	0.15	0.03	0.016				
Hip abduction	Wt.	0.16	0.16	<0.001	None	None	—	—	None	None	—	—
Hip adduction	Wt.	0.60	0.60	<0.001	Speed	0.02	0.02	0.039	Ht. (–)	0.13	0.13	<0.001
	Ht. (–)	0.61	0.01	0.019					Speed	0.15	0.02	0.031
Hip internal rotation	Wt.	0.31	0.31	<0.001	Speed	0.03	0.03	0.015	Speed	0.03	0.03	0.026
	Speed	0.34	0.03	0.013								
Hip external rotation	Wt.	0.15	0.15	<0.001	Speed	0.07	0.07	<0.001	Speed	0.07	0.07	0.001
	Speed	0.20	0.05	0.001					Wt. (–)	0.09	0.02	0.049
Knee flexion	Speed	0.08	0.08	<0.001	Speed	0.11	0.11	<0.001	Speed	0.11	0.11	<0.001
	Ht.	0.15	0.07	<0.001					Wt. (–)	0.13	0.02	0.026
Knee extension	Wt.	0.47	0.47	<0.001	Speed	0.09	0.09	<0.001	Speed	0.09	0.09	<0.001
	Ht.	0.51	0.04	<0.001	Ht.	0.14	0.05	0.002				
	Speed	0.54	0.03	0.004								
Knee adduction	Wt.	0.45	0.45	<0.001	Ht.	0.05	0.05	0.003	None	None	—	—
	Ht.	0.48	0.03	0.002								
Ankle dorsiflexion	Wt.	0.82	0.82	<0.001	Ht.	0.22	0.22	<0.001	Speed	0.08	0.08	<0.001
	Ht.	0.85	0.03	<0.001	Speed	0.29	0.07	<0.001	Wt. (–)	0.1	0.02	0.037
	Speed	0.86	0.01	0.001								

Wt. = weight, Ht. = height, None = no variable entered the equation, (–) = negative coefficient.

Males and females were significantly different in height, weight, and all 10 unnormalized joint moments (Tables 1 and 4). Normalizing by body mass resulted in six out of 10 moments still exhibiting significant differences between males and females ranging from 5% to 25%. Normalizing by body weight times height resulted in two moments still showing significant differences, hip abduction and hip adduction, with the disparity between genders being 18% and 14%, respectively.

4. Discussion

The two normalization techniques investigated in this study were both successful in reducing the effects of height and weight on peak joint moments during normal gait. With the exception of the hip adduction moment normalized by body weight times height and the ankle moment normalized by body mass, height and weight accounted for at most 6% of the variance in the moments. Differences in the moments due to gender were more successfully reduced using the body weight times height normalization method.

The results of our study are restricted to these two normalization methods. Other investigators have utilized a body weight times leg length normalization method (Chao et al., 1983; Kadaba et al., 1989); however, data on leg length were not collected on our subjects. It is likely that body weight times height and body weight times leg length would be equally effective in normalization since leg length has been used as a surrogate measure for height (Trotter and Gleser, 1952). We also did not evaluate other scaling strategies, such as dynamic/mechanical/elastic (Pierrynowski and Galea, 2001) because they also rely on leg length, are not commonly used, and have only been evaluated in 10 subjects.

The effectiveness of the normalization methods in the present study were tested in normal adult subjects. The heights and weights of both the males and females were highly representative of the adult US population, ranging from the 5th to the 95th percentile with the mean heights and weights for males were between the 50th and 75th percentiles and for females, 25th to 50th percentile and 50th to 75th percentile, respectively (Center for Disease Control-NHANES). Additional information might be gained if these analyses were extended to other populations.

One possible explanation for why height explained 13% of the variability in the hip adduction moment normalized by body weight times height is the significant

Table 3
Univariate Pearson correlations for unnormalized and normalized peak joint moments. Values are reported as $r^2 (p < 0.05)$

Peak Joint Moment		Unnormalized		Body mass normalized		Body weight times height normalized	
		r^2	Sig.	r^2	Sig.	r^2	Sig.
Hip flexion	Height	0.23	<0.001	—	—	—	—
	Weight	0.36	<0.001	—	—	—	—
	Speed	0.11	<0.001	0.18	<0.001	0.18	<0.001
Hip extension	Height	0.18	<0.001	—	—	—	—
	Weight	0.18	<0.001	—	—	0.06(−)	0.001
	Speed	0.08	<0.001	0.11	<0.001	0.10	<0.001
Hip abduction	Height	0.13	<0.001	—	—	—	—
	Weight	0.17	<0.001	—	—	—	—
	Speed	—	—	—	—	—	—
Hip adduction	Height	0.14	<0.001	—	—	0.13(−)	<0.001
	Weight	0.61	<0.001	—	—	—	—
	Speed	—	—	0.03	0.04	—	—
Hip internal rotation	Height	0.16	<0.001	—	—	—	—
	Weight	0.31	<0.001	—	—	—	—
	Speed	0.03	0.04	0.04	0.02	0.03	0.03
Hip external rotation	Height	0.10	<0.001	—	—	—	—
	Weight	0.16	<0.001	—	—	—	—
	Speed	0.06	0.003	0.08	<0.001	0.07	0.001
Knee flexion	Height	0.09	<0.001	—	—	—	—
	Weight	0.07	<0.001	—	—	0.03(−)	0.04
	Speed	0.09	<0.001	0.12	<0.001	0.11	<0.001
Knee extension	Height	0.31	<0.001	0.06	0.001	—	—
	Weight	0.48	<0.001	—	—	—	—
	Speed	0.04	0.01	0.10	<0.001	0.10	<0.001
Knee adduction	Height	0.30	<0.001	0.05	0.003	—	—
	Weight	0.45	<0.001	—	—	—	—
	Speed	—	—	—	—	—	—
Ankle dorsiflexion	Height	0.49	<0.001	0.22	<0.001	—	—
	Weight	0.83	<0.001	0.04	0.01	0.03(−)	0.05
	Speed	—	—	0.10	<0.001	0.09	<0.001

A dashed line,—, indicates no significance and a minus sign within parentheses (−) indicates a negative correlation.

Table 4
Peak external moment values for males and females (mean ± standard deviation)

	Unnormalized moments (N m)			Body mass normalized moments (N m/kg)			%Body weight times height normalized moments (unitless)		
	Males	Females	p-value	Males	Females	p-value	Males	Females	p-value
Hip flexion	75.0±22.3	59.2±19.7	<0.001*	0.93±0.26	0.91±0.25	0.623	5.3±1.5	5.6±1.5	0.255
Hip extension	52.2±18.7	41.5±13.6	<0.001*	0.65±0.21	0.65±0.21	0.955	3.7±1.2	4.0±1.3	0.148
Hip abduction	22.4±11.2	13.5±7.1	<0.001*	0.28±0.14	0.21±0.11	0.001*	1.6±0.8	1.3±0.7	0.016*
Hip adduction	64.7±16.3	56.8±17.1	0.004*	0.80±0.13	0.87±0.14	0.002*	4.6±0.8	5.3±0.8	<0.001*
Hip internal rotation	12.4±4.1	9.9±3.4	<0.001*	0.15±0.04	0.15±0.04	0.938	0.9±0.2	1.0±0.3	0.088
Hip external rotation	9.2±3.6	6.6±2.6	<0.001*	0.12±0.04	0.10±0.04	0.072	0.7±0.33	0.6±0.2	0.521
Knee flexion	38.4±18.3	25.4±12.2	<0.001*	0.49±0.24	0.40±0.19	0.013*	2.8±1.4	2.5±1.2	0.120
Knee extension	45.0±13.0	33.0±9.6	<0.001*	0.56±0.14	0.51±0.11	0.024*	3.2±0.8	3.1±0.7	0.725
Knee adduction	42.3±11.3	30.6±9.1	<0.001*	0.52±0.12	0.47±0.11	0.005*	3.0±0.7	2.9±0.7	0.415
Ankle dorsiflexion	132.6±26.1	100.3±20.1	<0.001*	1.64±0.17	1.55±0.13	<0.001*	9.3±0.9	9.5±0.7	0.150

*Indicates a statistically significant difference ($p < 0.05$) between males and females.

correlation between height and weight. By dividing out weight, or body mass, which is common to both methods, the anthropometric variability in the population due to height may have already been partially accounted for since height was correlated with weight. Thus, dividing by height in addition to weight may have overcorrected for this moment. This would account for why height was negatively correlated with this moment. It is feasible that the frontal plane hip adduction moment may also be less affected by height than by other parameters not considered in the present study such as pelvic width.

When normalizing the ankle dorsiflexion moment by body mass, height still accounted for 22% of the variance in this moment. In this case, dividing out weight may not be sufficient, and the addition of height to the normalization method may be necessary in order to account for the anthropometric differences due to height. Sagittal plane moments such as ankle dorsiflexion may be more influenced by height or other factors related to it such as foot length than weight.

The body weight times height normalization method was more effective in reducing differences due to gender than the body mass method. Since height was significantly different between males and females, the inclusion of height in the normalization scheme was important for diminishing these differences. However, neither method reduced gender differences for the frontal plane hip moments, indicating that anatomical variations such as pelvic width and shape or femoral geometry may also contribute to the variance in joint moments.

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