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Predicting peak kinematic and kinetic parameters from gait speed

Jennifer L. Lelas [a,*], Gregory J. Merriman [a], Patrick O. Riley [a,b], D. Casey Kerrigan [a,b]

[a] Center of Rehabilitation Science, Spaulding Rehabilitation Hospital, 125 Nashua Street, 02114 Boston, MA, USA
[b] Department of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, MA, USA

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Abstract

Objective: The aim of this study is to assess the predictability of the relationships between gait speed and common peak sagittal plane parameters in order to provide a set of reference parameter values. *Design*: Lower extremity biomechanical data were collected in 64 healthy adults while walking barefoot at his/her comfortable walking speed, then at self-selected fast, slow and very slow speeds. Twenty seven peak joint parameter values were plotted and regressed as a function of gait speed. *Discussion*: While most parameters change with increasing gait speed, in general, the kinetic parameters had better predictability than the kinematic parameters. Most of the power parameters were found to have a quadratic relationship with gait speed. Of the moment parameters, four had a linear relationship with gait speed, while four had a quadratic one. These relationships shown in the tables and graphs here can be used as a reference for 'normal' gait parameter values.

Keywords: Gait; Velocity; Biomechanical; Regression; Kinematics; Kinetics

1. Introduction

A reference set of 'normal' gait parameter values provides an invaluable tool within the realm of clinical gait analysis as a basis of comparison when deciding on treatment for abnormal and/or pathological gait. It is becoming more common to make allowances for the effect of gait speed on these gait parameters when making these comparisons, since patients tend to walk slower than their healthy counterparts [1–4]. To do this, one must know or be able to predict each reference value at a wide range of walking velocities. As it is generally accepted that gait parameters follow a consistent pattern of change in response to varying gait speed, [5] we believe it possible to model the pattern for each parameter and predict its value at any given walking velocity. Much has been done in an attempt to characterize the effect of gait speed on temporal and kinematic gait parameters. This work has shown that although the temporal parameters exhibit characteristic and predictable relationships with gait speed [6–10], there are varying conclusions as to the existence of the relationships between certain kinematic gait parameters and gait speed [5,10–12]. Studies of the dependency of kinetic gait parameters on gait speed are relatively limited, generally focusing only on one or two specific kinetic parameters [13,14].

The overall goal of this study was to assess the predictability of the relationships between gait speed and 27 common peak sagittal plane kinematic and kinetic parameters to provide a set of reference values. Specifically, we aimed to validate any existing relationships known for many of the kinematic and a few of the kinetic peak sagittal plane parameters. For those where no previous known relationship with gait speed is documented, we aimed to derive these relationships. Finally, we attempted to present all the results together in a clear, concise manner to provide a quick reference for comparison with and interpretation of pathological gait.

* Corresponding author. Tel.: +1-617-573-2728; fax: +1-617-573-2769
E-mail address: jlelas@partners.org (J.L. Lelas).

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2. Methods

Sixty four healthy adults between the age of 19 and 40 years (mean age 28.1 (5.9) years, mean weight 65.7 (15.7) kg and mean height 1.69 (0.10) m) with no known neurologic, orthopedic or cardiopulmonary problems volunteered for this study. Subjects were recruited by flyers and notices throughout the Partners HealthCare System. The study was approved by the Spaulding Rehabilitation Hospital Internal Review Board and informed consents were obtained from all subjects. The subjects were asked to walk barefoot along a 10 m gait laboratory walkway at four speeds. Each subject was first asked to walk at his/her own comfortable pace. They were then asked to walk at a self-selected pace faster than the comfortable pace and then at a self-selected pace slower than the comfortable pace. Finally, they were asked to walk at a very slow speed approximating 0.5 m/s.

Hip, knee and ankle kinematic and kinetic values were obtained bilaterally over three trials for each of the four conditions. A six camera video-based motion analysis system (VICON 512 system)[a] and two staggered force platforms[b] embedded in the walkway were used for this analysis based on standard procedures [15–19]. Joint angle motion was studied in all three planes and reported in degrees. External joint moments were computed using a commercially available full-inverse dynamics model, VICON Clinical Manager[a], and based on anthropometric characteristics and derived linear and angular velocity and accelerations of the lower limb, as well as ground reaction force and joint center position estimates. Joint moments and powers were normalized for body weight and height and reported in Newton-meters per kilogram-meters. Gait speed was utilized both as absolute walking speed in meters per second and normalized to leg length in meters per second-meters.

Joint kinematic and kinetic data were plotted over the gait cycle (0–100 at 2% intervals). For each condition, data from three right trials and three left trials were averaged together to obtain an average for each peak joint kinematic and kinetic parameter value. Peak kinematic and kinetic values were compared using regression analyses to evaluate potential relationships between gait speed and each peak value. First, a linear regression was fit to each parameter. The data was clustered by subject to account for repeated observations from the same subject at different speeds. A linktest was then performed to help determine whether the regression model was acceptable (a linktest assesses whether the model is correctly specified [20]). For any parameter in which the linktest showed the model to be insufficient, a quadratic regression was then fitted to the parameter and the linktest performed again. A multiple regression was performed on peak knee extension moment terminal stance as a function of gait speed and peak ankle dorsiflexion moment. Similarly, first a linear regression and then a quadratic one (for any parameter that was not correctly specified with a linear one) was run for each parameter and normalized gait speed. A multiple regression between each parameter and both absolute gait speed and leg length was also run first as a linear and then as a quadratic regression as described above. All statistical evaluations were performed using the software program Stata 6.0[c] and statistical significance was defined as $P < 0.05$ for all regression analyses.

3. Results

Each peak of the plots of motion, moments and powers at the ankle, knee and hip were evaluated for a total of 27 common peak sagittal plane parameters. Of these 27 parameters, ten were motion measures, eight were moment measures and the remaining nine were power measures. The equations and their R^2 values resulting from the regression analysis with absolute gait speed for each of these kinematic and kinetic parameters are presented in Tables 1 and 2, respectively. The results for the regression with normalized gait speed and the multiple regression with gait speed and leg length did not show overall improvement and were not substantially different in individual values from those obtained when regressing on raw gait speed; therefore, they have not been tabularized.

As seen in Table 1, in general, the linear and quadratic regressions resulted in a poor fit of the data for each kinematic parameter, although a linktest verified that each model was correctly specified. The kinetic data parameters, however, generally showed a better relationship with gait speed than the kinematic parameters, as seen in Table 2. Of the moment parameters, four were found to have a linear relationship with gait speed, including peak external hip flexion moment swing, peak external knee flexion moment loading response, peak external knee flexion moment pre-swing and peak external knee extension moment terminal stance. In the remaining four moment parameters and seven of the power parameters, a linktest showed that the relationship between each parameter and gait speed was not correctly specified by a linear regression; however, each was sufficiently described by a quadratic regression. Of the two remaining power parameters, peak knee power absorption loading response had a linear relationship with gait speed and peak ankle power absorption had a 3rd-order polynomial relationship with gait speed. Because the kinematic relationships were not strong, only the kinetic parameters were plotted as a function of gait speed in Figs. 1–17.

4. Discussion

In general, we found the peak sagittal plane kinematic parameters to have poor predictive relationships with gait speed. Winter et al. also reported little variation in joint kinematics at increasing cadences, except for minor increases in peak knee flexion during loading response [5]. We also observed an increase in peak knee flexion during loading response with increased speed consistent with that reported by others [10,12,21]. Moreover, we found a moderately predictive quadratic correlation between peak knee flexion during loading response and gait speed ($R^2 = 0.6000$). This moderate correlation in knee flexion angle with increasing gait speed during loading response could be an indication of the need for greater shock absorption at higher gait speeds. Peak knee flexion in swing also increased with increased walking speed, similar to the results seen by Oberg et al. [12] with a moderately predictive quadratic relationship of $R^2 = 0.4365$. Kirtley et al. reported similar correlation coefficients of $R = 0.78$ ($R^2 = 0.60$) and $R = 0.66$ ($R^2 = 0.43$) for peak knee flexion in loading response and swing, respectively, while predicting linear relationships for these two knee parameters [14]. However, our regression values were obtained from quadratic regressions, not linear ones. Additionally, we found a significant relationship between gait speed and both peak hip flexion and extension ($P < 0.0001$ for both). While these models were correctly specified as linear ones, the predictability of these two parameters were poor ($R^2 = 0.2403$ for peak hip flexion and $R^2 = 0.1360$ for peak hip extension). Previous studies also demonstrated an increase in peak hip extension with increased gait speed [22,23] and attempted to model it with a linear regression, but no correlation coefficient was provided [13].

While there were poor relationships between peak sagittal plane kinematic data and gait speed for most parameters, the peak sagittal plane kinetic parameters generally had a predictive dependency on gait speed.

Table 1
Peak sagittal plane kinematic parameter regression equations (v = velocity [m/s])

Parameter		Equation	R^2
Peak Hip Flexion	Degrees	$7.382v+23.8122$	0.2403
Peak Hip Extension	Degrees	$5.1143v+3.817958$	0.1360
Peak Knee Extension Before Initial Contact	Degrees	$-11.0v^2+31.0857v-22.43514$	0.3684
Peak Knee Flexion Loading Response	Degrees	$-2.84v^2+19.5885v-4.001339$	0.6000
Peak Knee Extension Terminal Stance	Degrees	$2.99v^2-6.0251v+3.298476$	0.0617
Peak Knee Flexion Swing	Degrees	$-3.19v^2+14.9165v+44.08403$	0.4365
Peak Ankle PlantarFlexion Loading Response	Degrees	$-1.7583v+9.190961$	0.0496
Peak Ankle DorsiFlexion Mid Stance	Degrees	$-2.4v+13.62415$	0.1048
Peak Ankle PlantarFlexion	Degrees	$3.7834v+12.88073$	0.0870
Peak Ankle DorsiFlexion Swing	Degrees	$4.16v^2-10.7498v+10.03869$	0.1110

Table 2
Peak sagittal plane kinetic parameter regression equations (v = velocity [m/s])

Parameter	Units	Equation	R^2
Peak Hip Flexion Moment Stance	Nm/kgm	$0.112v^2+0.2116v+0.006286$	0.8130
Peak Hip Extension Moment	Nm/kgm	$0.0590v^2+0.2044v+0.1234817$	0.7974
Peak Hip Flexion Moment Swing	Nm/kgm	$0.5741v-0.2010233$	0.8870
Peak Knee Flexion Moment Loading Response	Nm/kgm	$0.3312v-0.1617144$	0.7267
Peak Knee Extension Moment Terminal Stance	Nm/kgm	$0.0543v+0.2161687$	0.1105
Peak Knee Flexion Moment Pre-Swing	Nm/kgm	$0.1460v-0.0373174$	0.8861
Peak Knee Extension Moment Swing	Nm/kgm	$-0.0397v^2+0.344v-0.0929555$	0.9221
Peak Ankle DorsiFlexion Moment	Nm/kgm	$-0.0530v^2+0.2822v+0.6501515$	0.4849
Peak Hip Power Generation Loading Response	W/kgm	$0.823v^2-0.9638v+0.4813577$	0.7590
Peak Hip Power Absorption	W/kgm	$0.316v^2-0.2698v+0.1848337$	0.6933
Peak Hip Power Generation Pre-Swing	W/kgm	$0.410v^2+0.4939v-0.1807213$	0.8861
Peak Knee Power Absorption Loading Response	W/kgm	$1.24994v-0.7875296$	0.7002
Peak Knee Power Generation Mid-Stance	W/kgm	$0.225v^2+0.0376v+0.0668056$	0.7711
Peak Knee Power Absorption Pre-Swing	W/kgm	$0.400v^2+0.0154v+0.0202647$	0.9165
Peak Knee Power Absorption Swing	W/kgm	$0.379v^2+0.2765v-0.0711721$	0.8377
Peak Ankle Power Absorption	W/kgm	$0.168v^3-0.969v^2+1.6089v+0.243167$	0.1841
Peak Ankle Power Generation Pre-Swing	W/kgm	$-0.243v^2+2.4996v-0.7180648$	0.8523

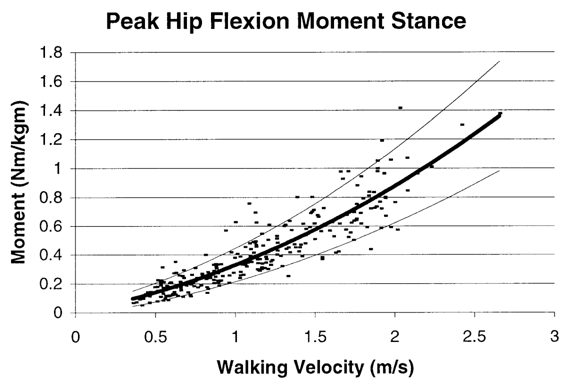

Fig. 1. Peak hip flexion moment stance as a function of gait speed (▬ regression line, — ±S.E.).

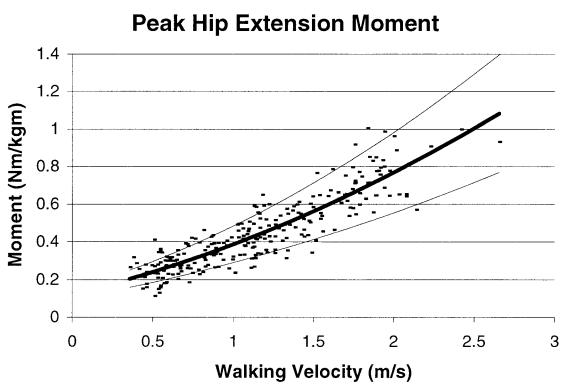

Fig. 2. Peak hip extension moment as a function of gait speed (▬ regression line, — ±S.E.).

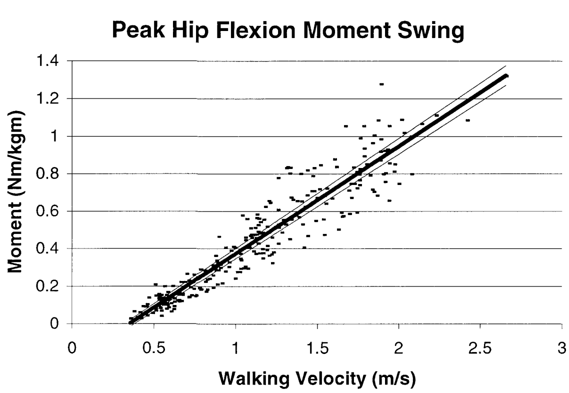

Fig. 3. Peak hip flexion moment swing as a function of gait speed (▬ regression line, — ±S.E.).

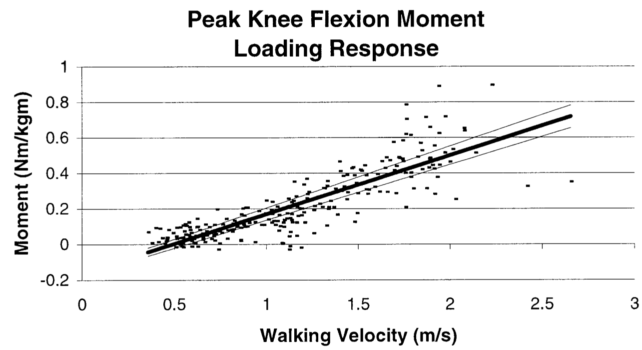

Fig. 4. Peak knee flexion moment loading response as a function of gait speed (▬ regression line, — ±S.E.).

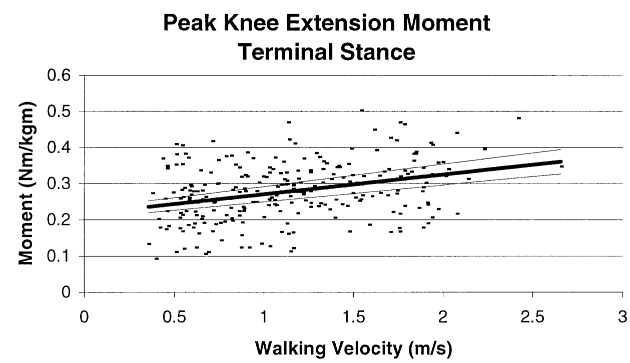

Fig. 5. Peak knee extension moment terminal stance as a function of gait speed (▬ regression line, — ±S.E.).

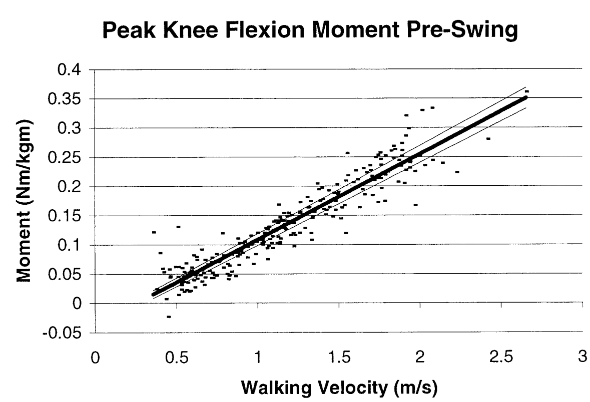

Fig. 6. Peak knee flexion moment pre-swing as a function of gait speed (▬ regression line, — ±S.E.).

Crowninshield et al. found that the peak external hip moment had a predictive polynomial relationship with gait speed, [13] as did we ($R^2 = 0.8130$ and $R^2 = 0.8870$ in stance and swing, respectively). Kirtley et al. reported a correlation coefficient of $R = 0.86$ ($R^2 = 0.74$) for linear regression of the peak external knee flexion moment in stance [14] similar to our R^2 of 0.7267.

In fact, we found relatively strong relationships with gait speed ($R^2 \geq 0.7267$) for each moment parameter except peak external knee extension moment in terminal stance ($R^2 = 0.1105$) and peak external ankle dorsiflexion moment ($R^2 = 0.4849$). Although the relationship with gait speed is not strong for these two parameters, both increase with increasing gait speed, as seen in Figs. 5 and 8. The fact that these trends are visible and statistically significant ($P < 0.0001$ for both), yet the data are widely scattered about the regression line, suggests that other factors may also influence these

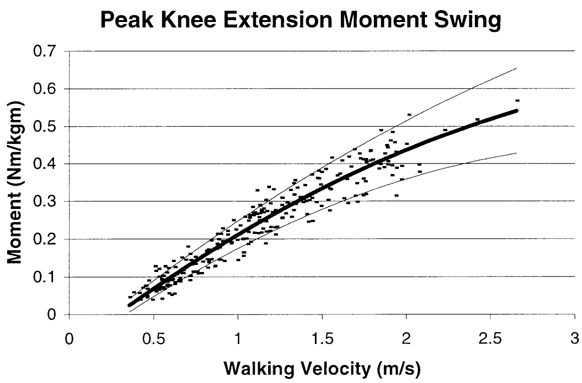

Fig. 7. Peak knee extension moment swing as a function of gait speed (▬ regression line, — ±S.E.).

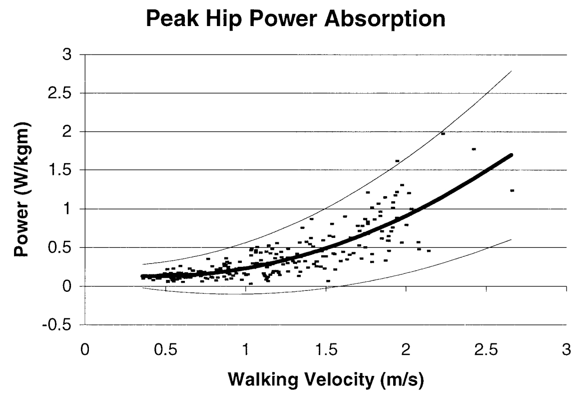

Fig. 10. Peak hip power absorption as a function of gait speed (▬ regression line, — ±S.E.).

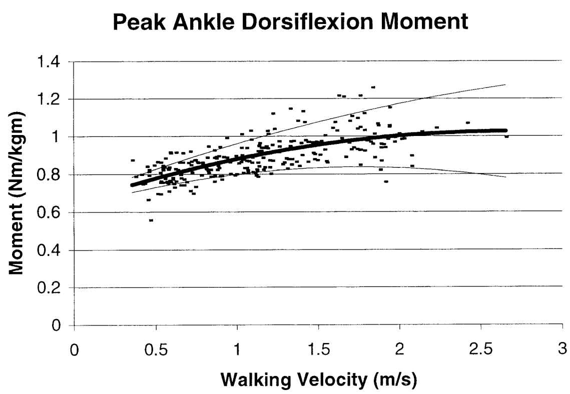

Fig. 8. Peak ankle dorsiflexion moment as a function of gait speed (▬ regression line, — ±S.E.).

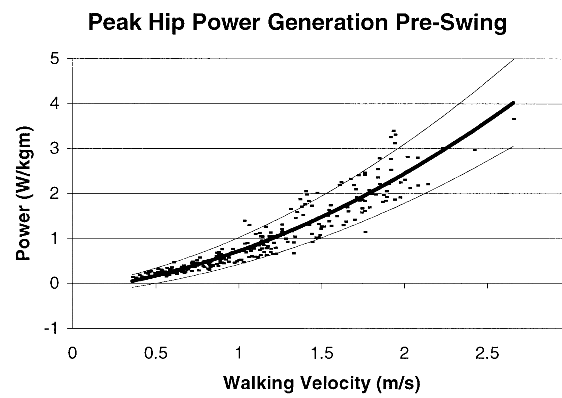

Fig. 11. Peak hip power generation pre-swing as a function of gait speed (▬ regression line, — ±S.E.).

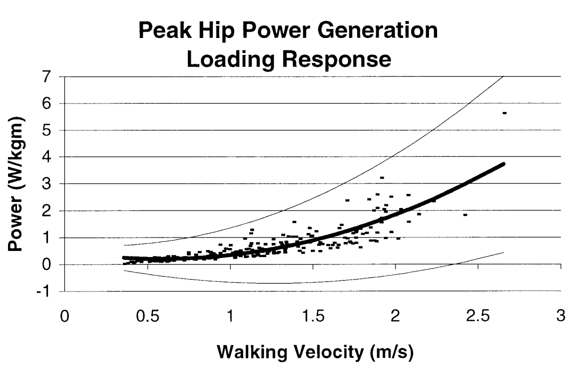

Fig. 9. Peak hip power generation loading response as a function of gait speed (▬ regression line, — ±S.E.).

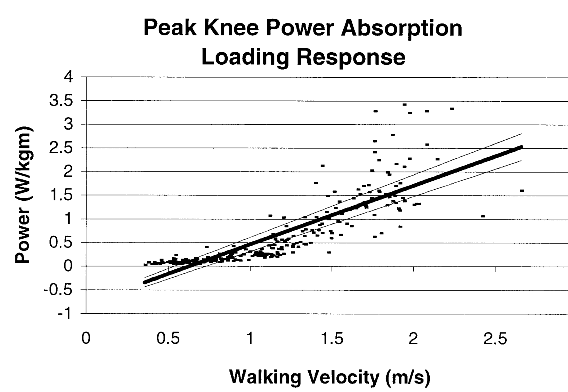

Fig. 12. Peak knee power absorption loading response as a function of gait speed (▬ regression line, — ±S.E.).

parameters. Simonsen et al. showed that a knee joint external extensor moment could be caused directly by a large external dorsiflexion moment about the ankle joint [24]. Since these are the two parameters with which there are poor relationships with gait speed, we then examined the influence of one on the other. The peak external knee extension moment in terminal stance was regressed as a function of both gait speed and peak external ankle dorsiflexion moment; however, the relationship remained quite weak with an $R^2 = 0.1604$.

The relationships between all peak sagittal plane power parameters and gait speed was a quadratic one, except peak ankle power absorption and peak knee power absorption loading response. All showed a fairly

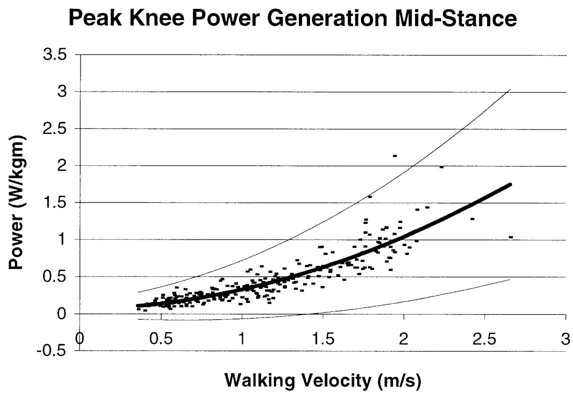

Fig. 13. Peak knee power generation mid-stance as a function of gait speed (▬regression line, — ±S.E.).

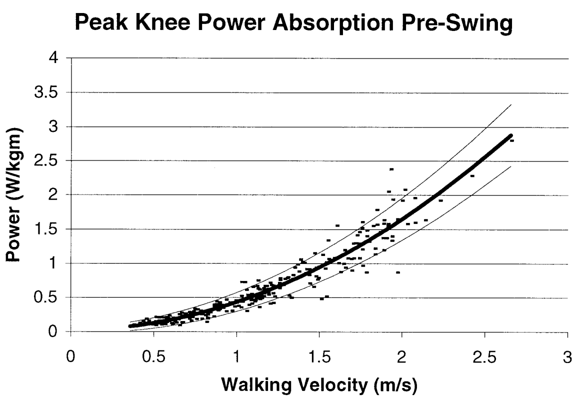

Fig. 14. Peak knee power absorption pre-swing as a function of gait speed (▬ regression line, — ±S.E.).

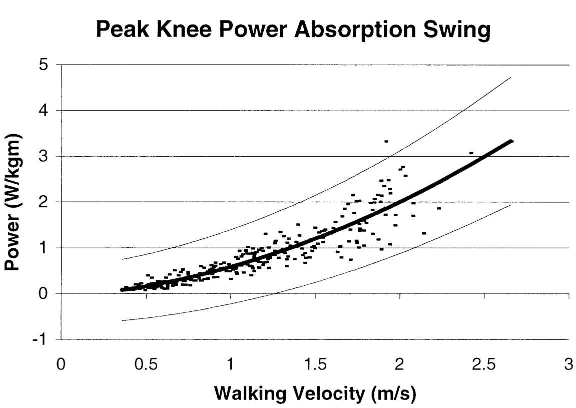

Fig. 15. Peak knee power absorption swing as a function of gait speed (▬ regression line, — ±S.E.).

high dependence on gait speed with R^2 values of 0.6933 or greater except peak ankle power absorption ($R^2 = 0.1841$).

In summary, the statistically significant relationships found here indicate that taking gait speed into consideration when evaluating patients by these parameters may provide more accurate information. We found that while most parameters change with increasing gait

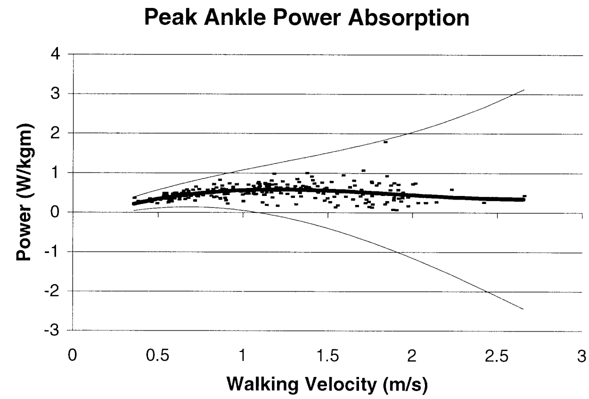

Fig. 16. Peak ankle power absorption as a function of gait speed (▬ regression line, — ±S.E.).

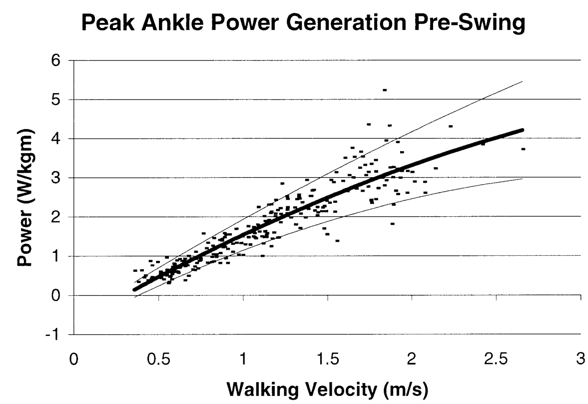

Fig. 17. Peak ankle power generation pre-swing as a function of gait speed (▬ regression line, — ±S.E.).

speed, in general, the kinetic parameters had better predictability with gait speed than did the kinematic parameters. These relationships and their corresponding equations, shown in the tables and graphs here, can be used as a quick reference for normative, nondisabled reference values.

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