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Test of two prediction methods for minimum and maximum values of gait kinematics and kinetics data over a range of speeds

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ABSTRACT

Background: Minimum and maximum values of gait kinematics and kinetics data are commonly used to quantitatively describe a walking pattern.

Research question: The purposes of this study were to determine the effect of speed on the minimum and maximum values of gait kinematics and kinetics variables and to test two prediction methods for the estimation of these minimum and maximum values at different gait speeds.

Methods: An open dataset with the data of 24 healthy adults (age: 27.6 ± 4.4 years, height: 171.1 ± 10.5 cm, body mass: 68.4 ± 12.2 kg) walking on a treadmill at eight gait speeds was employed in this study. The minimum and maximum angles and moments of the hip, knee, and ankle joints were extracted from speed-dependent prediction curves solely for the minimum and maximum values (PEAK method) and from speed-dependent prediction curves for the entire gait cycle (CYCLE method). The overall error, computed as the root-mean-square error (RMSE), for the minimum and maximum values predicted by these two methods were compared with the experimental true values.

Results: The RMSEs for the joint angles were PEAK: 3.86 ± 1.21°, CYCLE: 3.88 ± 1.18° and for the joint moments were PEAK: 0.129 ± 0.052 Nm/kg, CYCLE: 0.131 ± 0.052 Nm/kg.

Significance: The two prediction methods tested can be used to estimate the minimum and maximum values of biomechanical gait variables at a certain speed.

1. Introduction

In gait analysis, it is common to compare individuals walking at different speeds, e.g., [1,2]. Since speed itself affects biomechanical gait variables [3–5], isolating the effect of pathology or aging from the gait speed when comparing the gait patterns between different populations is problematic. A solution is to employ prediction methods for estimating joint kinematics and kinetics variables [6–9] or gait indices [10] of normative gait data at any given speed. The general approach of these methods is to acquire experimental data at different gait speeds and then adjust regression models to the gait data versus speed to determine prediction equations with speed as the predictor variable.

Minimum and maximum values of gait variables are commonly used to quantify them, and there are at least two methods to predict these values at a given speed. In one method [7,8], hereafter referred to as the PEAK method, regression equations are adjusted directly to only the experimental minimum and maximum values of the gait data versus speed. However, these equations are only suitable for predicting the minimum and maximum values of a single desired speed. In a second method [9], hereafter referred to as the CYCLE method, regression equations are adjusted to the entire gait cycle versus speed (e.g., an equation at every 1% of the cycle for a given gait variable), and then the minimum and maximum values of this predicted gait cycle can be found. Although the CYCLE method might be more advantageous because it can predict data for the entire gait cycle, it might be less accurate than the PEAK method if one is only interested in the minimum and maximum values. Therefore, the goals of this study were to investigate the effect of gait speed on biomechanical variables and to test two prediction methods for the minimum and maximum values of gait patterns at different speeds.

2. Methods

The rationale is to use the normative reference data of healthy subjects with actual experimental data acquired at different gait speeds to test the prediction equations against these true values. For such, we used an open dataset [11] with the gait data of 24 healthy adults walking at different speeds (age: 27.6 ± 4.4 years, height:

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Table 1

Coefficients [β_0, β_1, β_2] for the quadratic regressions ($y = \beta_0 v^2 + \beta_1 v + \beta_2$) to the experimental minimum and maximum values of the hip, knee, and ankle joint angles and moments as function of gait speed (in the dimensionless unit) using the PEAK prediction method considering the mean of each subject (see Fig. 2). Also shown, the χ^2_{red} and R^2_{adj} goodness-of-fit metrics and the RMSE between the experimental values and the predicted values using the PEAK and CYCLE methods and LELAS equations.

Variable	PEAK coefficients [β_0, β_1, β_2]	χ^2_{red}	R^2_{adj}	PEAK RMSE	CYCLE RMSE	LELAS RMSE
Joint angles (°)						
Hip Flexion	[8.718, 11.655, 26.869]	34.629	0.187	5.026	5.057	7.497
Hip Extension	[14.115, −28.187, 1.192]	40.499	0.134	5.561	5.552	6.000
Knee Extension before initial contact	[24.860, −18.535, 4.726]	17.976	0.013	3.773	3.738	11.155
Knee Flexion loading response	[−17.274, 50.961, −2.238]	28.164	0.532	4.654	4.678	12.574
Knee Extension terminal stance	[−18.156, 15.728, −0.540]	20.708	0.000	3.845	3.886	5.141
Knee Flexion swing	[−64.024, 73.883, 43.734]	13.232	0.504	3.312	3.382	12.351
Ankle Plantarflexion loading response	[14.214, −6.218, −5.178]	9.029	0.071	2.608	2.607	4.136
Ankle Dorsiflexion mid stance	[−3.219, −3.302, 15.078]	9.640	0.070	2.639	2.723	2.812
Ankle Plantarflexion	[59.358, −75.635, 7.074]	40.283	0.324	5.149	5.079	7.187
Ankle Dorsiflexion swing	[33.183, −29.530, 12.490]	5.938	0.108	2.024	2.112	2.311
Joint moments (Nm/kg)						
Hip Flexion stance	[−1.477, −0.770, −0.264]	0.024	0.796	0.141	0.151	0.682
Hip Extension	[0.475, 0.925, −0.069]	0.014	0.741	0.107	0.114	0.165
Hip Flexion swing	[−0.871, −1.016, −0.063]	0.016	0.815	0.117	0.118	0.754
Knee Flexion loading response	[1.230, 0.826, −0.287]	0.049	0.617	0.193	0.192	0.393
Knee Extension terminal stance	[−0.024, −0.139, −0.411]	0.031	0.008	0.157	0.157	0.170
Knee Flexion preswing	[0.408, 0.141, −0.021]	0.008	0.391	0.062	0.061	0.136
Knee Extension swing	[0.430, −1.205, 0.049]	0.005	0.770	0.061	0.060	0.387
Ankle Dorsiflexion	[−1.816, 2.323, 0.947]	0.045	0.290	0.192	0.194	0.312

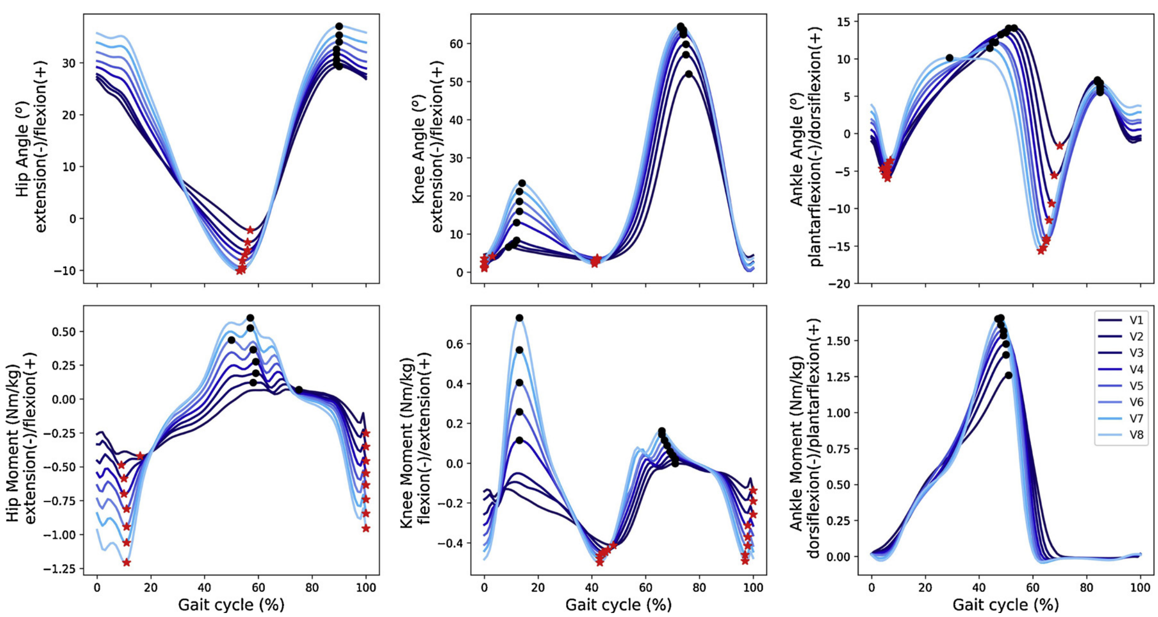

Fig. 1. Average patterns across subjects for the joint angles (top) and joint moments (bottom) of the experimental data and the minimum (*) and maximum (●) values of each mean curve at the eight gait speeds (V1–V8).

171.1 ± 10.5 cm, body mass: 68.4 ± 12.2 kg). These data were collected performing a standard three-dimensional gait analysis, where the subjects walked barefoot on a treadmill at eight different gait speeds as a percentage of her/his comfortable speed: 40%, 55%, 70%, 85%, 100%, 115%, 130%, and 145% (V1–V8), with gait speeds adjusted based on the dimensionless speed (Froude number) (Table 1, Supplementary material). The joint angles and joint moments data at the sagittal plane of the hip, knee, and ankle joints of each gait cycle were normalized to 0–100% with a step of 1%. At each gait speed, an average across the gait cycle trials was calculated for each subject and each biomechanical variable, and then the mean pattern across subjects and a 95% confidence interval (95% CI) for the mean were calculated. For each variable, the minimum and maximum values of the average curves of each participant in each speed was first defined, and then, the average values across participants were calculated. These values were detected at the same specific phases of the gait cycle utilized by LELAS and collaborators [7] and will be considered as the true experimental minimum and maximum values of the dataset (see Fig. 1), for which we will derive prediction equations based on the two methods, PEAK and CYCLE.

For the PEAK method, second-order polynomials were adjusted to the minimum and maximum experimental true values versus speed to directly obtain regression equations for the minimum and maximum values. For the CYCLE method, second-order polynomials were adjusted to every 1% of the experimental gait cycle data versus speed to obtain prediction curves for the entire gait cycle (for more details, see [9]), and minimum and maximum values at a desired speed were found for these predicted data. The second-order polynomial was adjusted by least squares, and its goodness of fit was verified with the adjusted coefficient of determination (R^2_{adj}), the reduced chi-squared (χ^2_{red}), and by examining the distribution of the residuals for the PEAK method.

For comparison with the literature, the minimum and maximum values will also be predicted with the equations presented in [7], hereafter referred to as LELAS equations.

The overall error of the predictions for the minimum and maximum values using the PEAK and CYCLE methods and LELAS equations across all gait speeds was computed as the RMSE between the experimental true values and the corresponding predicted values. The RMSE was calculated considering either the mean values of each subject and speed (Table 1); or the average values across subjects (RMSEall) (Supplementary material). A statistical difference ($p < 0.05$) between the values using the PEAK and CYCLE methods and LELAS equations at each gait speed (V1–V8) was ascertained when these predicted values were outside the 95% CI for the mean of the corresponding experimental true values. Additionally, to assess the performance of the prediction methods, a 10-fold cross-validation procedure was performed where the original dataset was divided into ten equal subsets with nine subsets used to train the predictor and one subset used to test.

3. Results

The average data for the experimental true minimum and maximum values based on the average of each subject and speed of the joint angles and moments versus gait speed and the regressions to these data are plotted in Fig. 2, and the corresponding statistics are shown in Table 1. Average data across all subjects are shown in the Supplementary material.

There were statistically significant differences between the experimental true values and the predicted values using the PEAK (knee flexion loading response and extension terminal stance moments) and CYCLE (hip extension, and knee flexion loading response and pre-swing moments) methods. For most variables, the experimental true values were significantly different from the values predicted with the LELAS equations (see Fig. 2). The mean-across-variables RMSE for the joint angles were PEAK: 3.86 ± 1.21°, CYCLE: 3.88 ± 1.18°, LELAS: 7.12 ± 3.79°, and for the joint moments were PEAK: 0.129 ± 0.052 Nm/kg, CYCLE: 0.131 ± 0.052 Nm/kg, LELAS: 0.375 ± 0.235 Nm/kg. Additionally, the 10-fold cross-validation presented an accuracy of 90.68% for the PEAK and 93.98% for the CYCLE method. Values for the RMSEall is shown in the Supplementary material.

4. Discussion

We observed that speed affected the minimum and maximum values of the joint angles and moments, and this effect was nonlinear at the range of speeds investigated. Previous studies [6,7,12] have also reported such an effect of speed, but, qualitatively, those reports described a more linear relationship between gait speed and biomechanical variables during gait than observed here.

The values predicted by the PEAK and CYCLE methods agreed with the experimental true values for most of the biomechanical variables, but overall, the error of the PEAK method in predicting the true values was lower than the CYCLE method. The fundamental difference between these two methods is that the PEAK method is based on always fitting the experimental true minimum and maximum values of the data. In contrast, because the CYCLE method is based on fitting data at certain percentages of the experimental data, likely the minimum and maximum values at different speeds will not coincide at the same percentage of the gait cycle.

The regression equations presented here can be readily used by anyone interested in predicting the minimum and maximum values of the joint angles and moments for reference data of healthy adults walking at any desired speed from 0.39 to 2.23 m/s; bear in mind that the independent variable for these equations, gait speed, should be specified as dimensionless speed (Froude number). Given the smaller errors in the prediction, if one is only interested in the minimum and maximum values, the regression equations based on the PEAK method is indicated.

The observed minimum and maximum values for most of the biomechanical variables investigated in this study are significantly

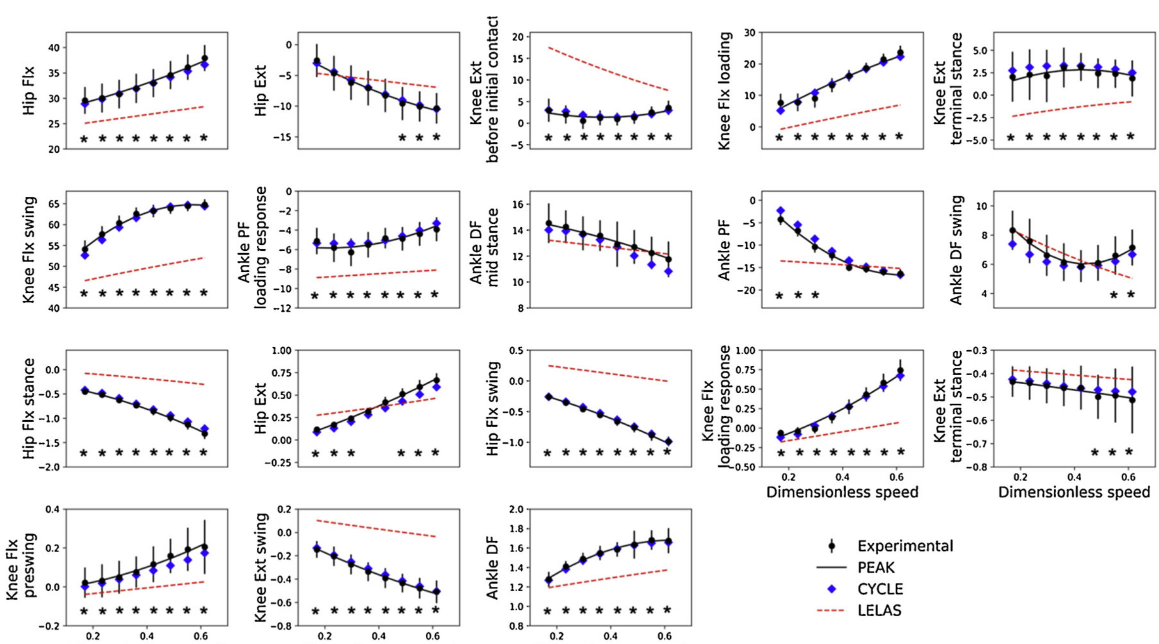

Fig. 2. Minimum and maximum values averaged of each subject of the experimental (●) hip, knee, and ankle joint angles (in °, first two rows) and joint moments (in Nm/kg, third and fourth rows) versus the dimensionless gait speed. The vertical bars indicate the 95% CI for each of these values. For each variable, the curves represent the quadratic regression to these values using the PEAK method (solid line) and the LELAS equations (dashed line). The corresponding values predicted by the CYCLE method are also shown (◆). Statistically significant differences between experimental true values and the values predicted with LELAS equations are marked with an asterisk.

different from the values predicted by LELAS equations [7]. Possible factors that might explain such a discrepancy are different surface conditions (treadmill *vs.* overground) and different data collection protocols between laboratories. This question deserves to be investigated in more detail because it may hamper the use of prediction equations for comparison to the gait data of a subject evaluated in a different laboratory.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.07.500.

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