Equations for predicting lower-limb joint kinematics and kinetics during human walking and running on slopes

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Introduction

Kinematic and kinetic data about slope walking and running is important for understanding human locomotion mechanics and for designing assistive devices such of passive orthoses and lower-limb wearable exoskeletons. Obtaining this information is typically done by using theoretical and empirical models with simplified representation of human gait, or in expensive experiments in a gait laboratory.

Aim

Our aim is to develop prediction equations for walking and running at kinematic and kinetic at slopes

Methods

Experimental protocols

In the experiment all participants walked and ran on an instrumented split-belt treadmill at a speed of 1.25 and 2.25 m/s (respectively) at five different grades for walking (0%, ±10%, ±15%) and running (0%, ±5%, ±10%). Motion and force data were collected at each of the grades.

Stage 1: Using Fourier series expansion to fit equations for joint kinematics and kinetics at each slope

In the first stage, we developed predication equations for walking and running at each of the five slopes separately (a total of 90 equations = 2 conditions (walk/run) x3 joint x5 slope x(angle, torque, power)), with a form of Fourier series of trigonometric functions. To find the equation parameters of the Fourier series expansion, we use optimization. To reduce the computational complexity we transformed the optimization into a linear problem (equation 1). The frequency value was calculated according to $\omega = 2\pi f = 2\pi \frac{1}{T} = 2\pi \frac{1}{100}$.

$$(1) \quad \beta_0 + \sum_{i=1}^{n} [\delta_i \times \sin(i\omega x) + \gamma_i \times \cos(i\omega x)]$$

Stage 2: Development of regression equations for lower-limb joint kinematics and kinetics as a function of stride percentage and ground slope

In the second stage, we aim to predict joint parameters as a function of percentages of a cycle and slope for each of the conditions (running/ walking). To achieve this goal, we fit a polynomial that models how the coefficients ($\beta_0, \delta_0, \gamma_0$) of equation 1 from stage 1 change as a function of the slope.

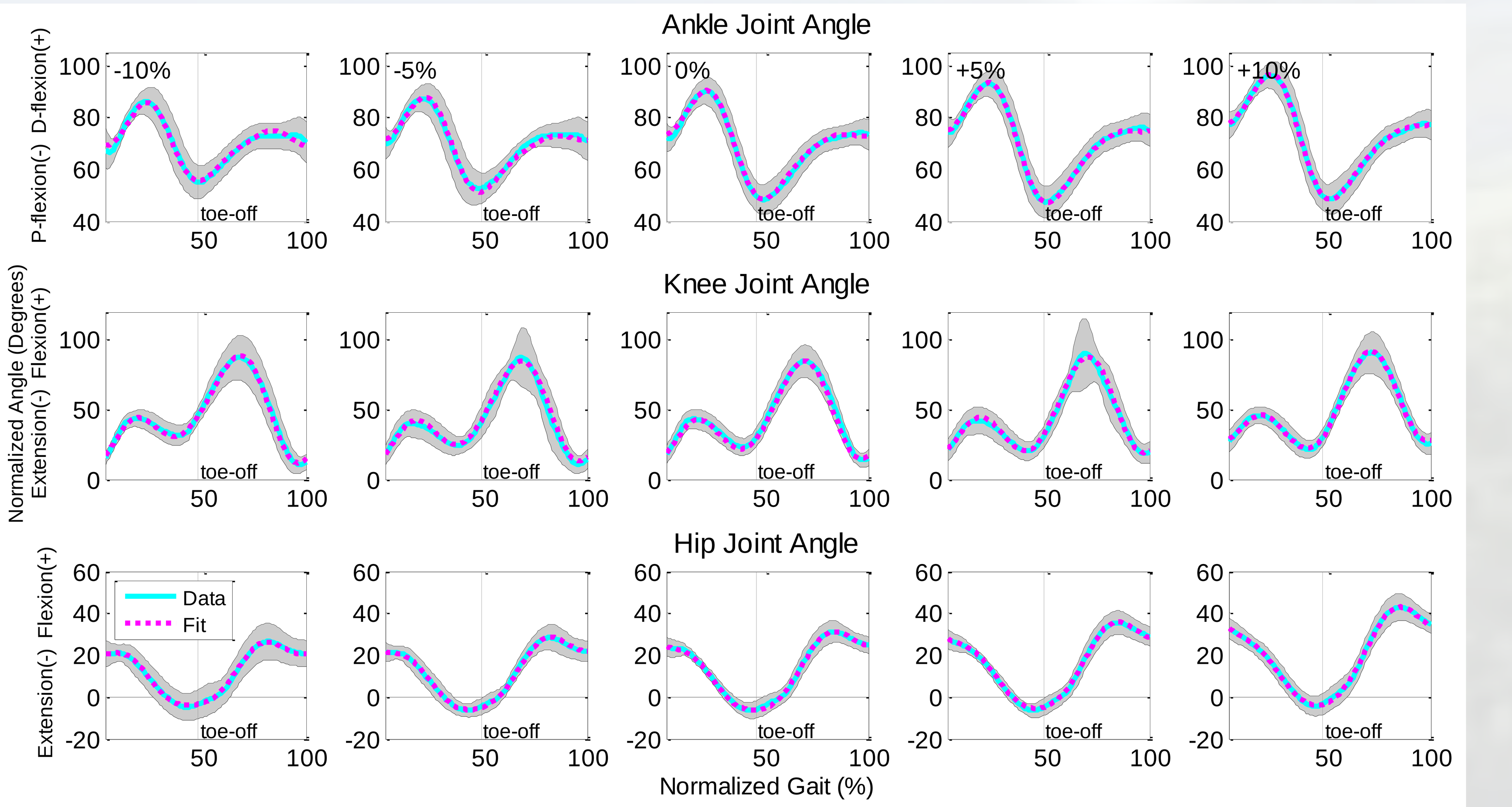
$$(2) \quad \beta_0 = \sigma_0 + \sum_{j=1}^{m} \sigma_j \times Slope^j \qquad (3) \quad \delta_i = \rho_{i0} + \sum_{j=1}^{m} \rho_{ij} \times Slope^j \qquad (4) \quad \gamma_0 = \mu_{i0} + \sum_{j=1}^{m} \mu_{ij} \times Slope^j$$

Results

Evaluation of regression equations for lower-limb joint kinematics and kinetics as a function of stride percentage and ground slope (Stage 2=final fit)

	Running		Walking	
Parameter	Adjusted R Square	RMSE	Adjusted R Square	RMSE
Ankle Angle[˚]	0.997	0.893	0.986	1.23
Knee Angle[˚]	0.996	1.778	0.988	2.82
Hip Angle[˚]	0.999	0.519	0.994	1.26
Ankle Moment[Nm/(kg*m)]	0.997	0.037	0.997	0.02
Knee Moment[Nm/(kg*m)]	0.998	0.020	0.994	0.02
Hip Moment[Nm/(kg*m)]	0.998	0.019	0.982	0.03
Ankle Power[W/(kg*m)]	0.994	0.141	0.981	0.09
Knee Power[W/(kg*m)]	0.975	0.206	0.966	0.09
Hip Power[W/(kg*m)]	0.989	0.045	0.977	0.03

Lower limb joint angles at each of ground slope regression equations as a function of stride percentage versus the experimental data.

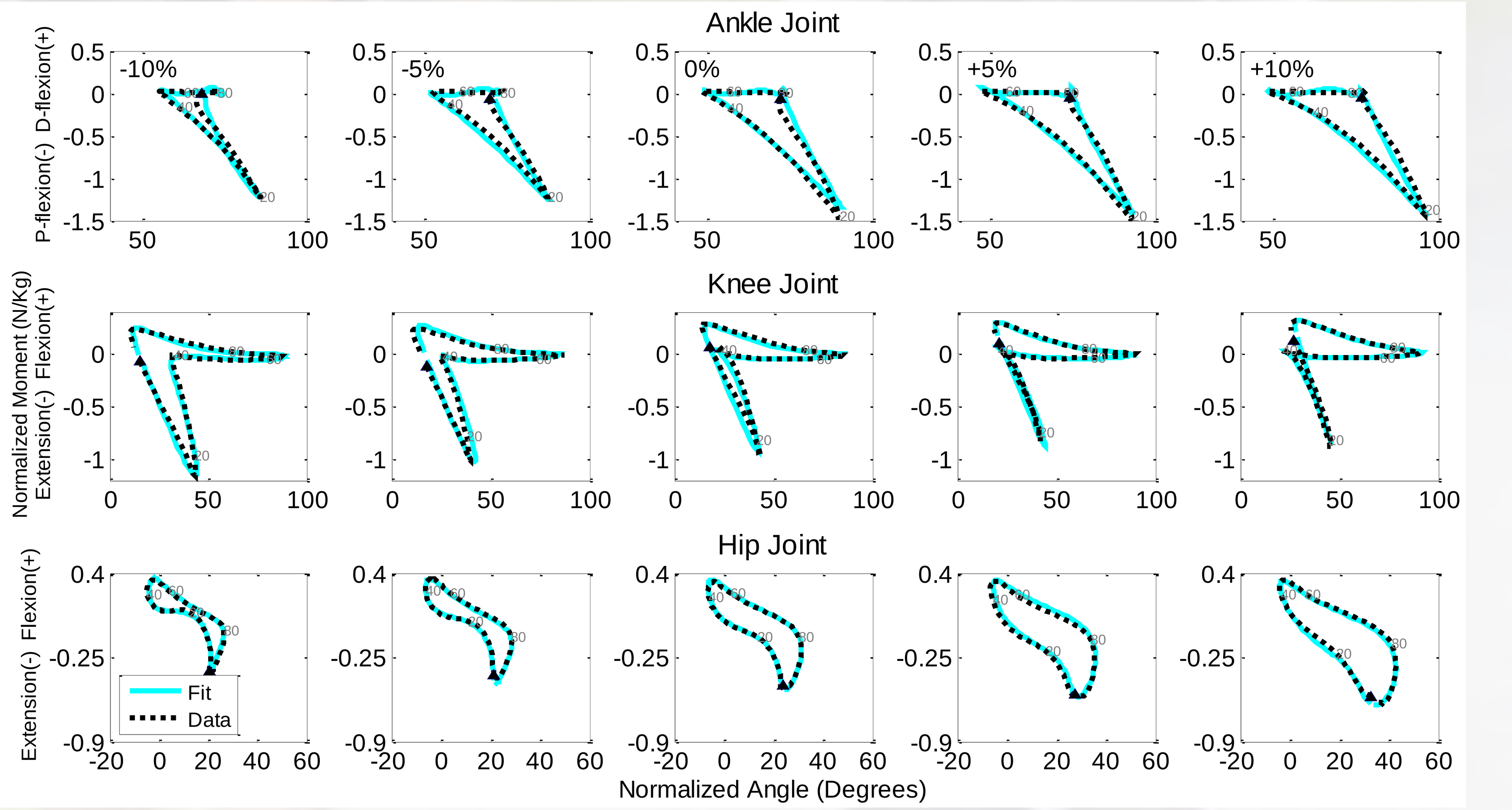


Example: knee angle prediction equations as a function of slope and location in the gait cycle (running)

$$(42.62+0.1Slope+0.04Slope^2) + (-18.63-0.31Slope-0.01Slope^2)\ \sin(\omega x) + (-10.84+0.7Slope)\ \cos(\omega x) + (16.13-0.17Slope-0.02Slope^2)\ \sin(2\omega x) + (-13.48-0.49Slope-0.003Slope^2+0.003Slope^3)\ \cos(2\omega x) + (2.22-0.06Slope)\ \sin(3\omega x) + (-0.97-0.03Slope)\ \cos(3\omega x)$$

Extending the approach: estimating joint quasi-stiffness from predicted moment-angle relations during running

Using the final predication equations, we plotted joint moment as a function of the angle versus the data from the experiments.



Discussion

This study presents prediction equations for leg kinematics and kinetics as a function of the slope during walking and running. The equations represent the data well and have high R^2 values (walking average of 0.984 (0.0104) and running average of 0.994 (0.0076)). The joint, angle, moment and power are similar in behavior and magnitude to results appearing in previous studies. These findings reinforce the idea that the equations could be used to simulate/generate walking and running data.