PREDICTION EQUATIONS FOR LEG KINEMATICS AND KINETICS DURING SLOPE RUNNING

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INTRODUCTION

Kinematic and kinetic data describing the dynamics of lower-limb joints are critical for understanding the neuromechanics and energetics of human locomotion, and for guiding the design of assistive devices (e.g. lower-limb exoskeletons). From a basic science perspective, studies have provided insight into the sources of metabolic energy consumption by relating joint kinetics to whole-body oxygen consumption [1]. From an applied science perspective, kinematic and kinetic data are important for the geometric and material properties of lower-limb orthoses [2] and of motors sizing for powered exoskeletons and prostheses [3], as well as for guiding control software in both powered exoskeletons [4] and prostheses [5].

Combining experimental approaches like motion capture and force measurements with rigid body models (i.e. inverse dynamics) provides a means for obtaining lower-limb joint kinematics and kinetics data. Many studies have addressed walking or running at typical speeds on level ground [1,6]. Yet data acquisition is expensive and time-consuming, and therefore available joint-level data is limited to only a small subset of speeds. The same holds for data from locomotion uphill and downhill. Additionally, relationships describing how lower-limb joint kinematics and kinetics depend on the phase of gait have not been documented using parametric-equations, which if developed could help fill in data gaps in the literature without requiring exhaustive data acquisition.

Using an experimental data set, our aim was thus to develop a comprehensive parametric model of lower-extremity joint kinematics and kinetics during human running up and down slopes.

METHODS

In two separate experiments, at two different labs (BGU and NCSU), sixteen healthy adults (6 females; 10 males; age = 24.56±3.16 years; height = 1.73±0.09 m; mass = 68.01±13.98 kg) ran on an instrumented split belt treadmill (FIT, Bertec, Columbus, OH, USA) at 2.25 m/s at nine grades (-10%, -7.5% -5%, -2.5%, 0%, +2.5% +5%, +7.5%, +10%). In each of the experimental conditions, force and motion data of at least 7 gait cycles (average = 20) were collected (MX40+, VICON, Oxford, UK or Oqus, Qualisys Medical AB®, Gothenburg, Sweden). Then the kinematics and kinetics of the leg joints were calculated using Visual3D software (C-motion Inc., Germantown, MD, USA). All kinematics and kinetics were normalized in time as percentages of one gait cycle. In addition, torque and power were normalized by the subject's height and weight.

Then based on a method by Mizrachi et al. [7] we developed the prediction equations for running in different slopes using data from randomly selected 14 subjects (7 from each group). Each of the above equations was developed in two phases: First, an equation was fitted for each of the five training slopes (-10%, -5%, 0%, 5%, 10%) separately (45 equations = 3 joint*5 slope*[angle, torque, power]), where for each joint and given slope the equation's input was the percentage of the gait cycle. Since gait exhibits periodic behavior, we used a Fourier series in the form of sine and cosine with $\omega=2\pi$ 1/100 to model these equations. Then, in the second phase, we modeled the change in value of each of the Fourier series coefficients as a function of the slope, using a polynomial. For both phases we developed an algorithm that found the best fit (Adjusted R^2), using the lowest order of series/polynomial. To test the prediction equations, we examined the two subjects who were not used in developing the equations. Also, we tested several slopes that were not included in the training set (-

7.5%, -2.5%, 2.5%, 7.5%). If the results of the test data fell within 3 standard deviations (SD) from the fit, we considered it as a successful fit. The 3SDs were calculated using the training data.

RESULTS AND DISCUSSION

The prediction equations had an Adjusted R^2 for the leg joint kinematics and kinetics ranging from 0.943 to 0.997. We also show that newly presented data (either for new subjects or new slopes), which were not used for the equations fitting, in most cases fell within 3 standard deviations from the prediction. Figure 1 is an example for the knee, at 5% slope of new subjects' data, and Figure 2 is an example for prediction on untrained subjects and slopes.

In addition, from our analysis we did not see differences between the male's and female's data. Furthermore, since the equations were developed based on data that were collected in two different sites, with different motion capture systems and with similar but not identical marker placements, we believe prediction equations are a good representation of the general healthy adult population.

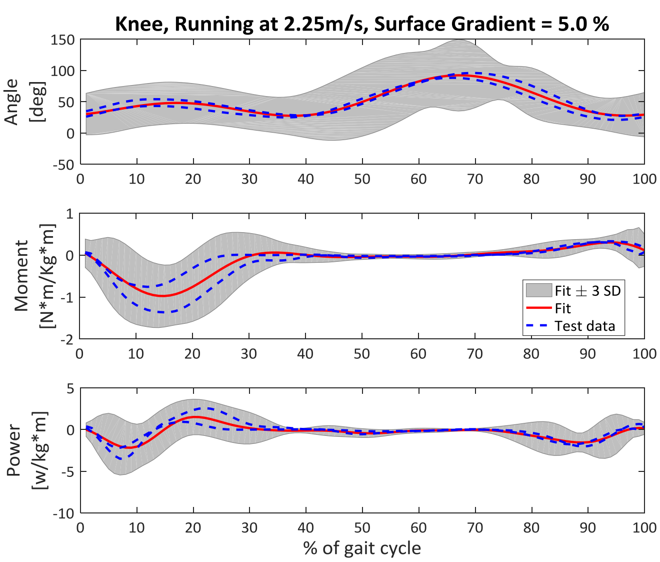

Figure 1: Test of the predictions using new subjects at a 5% slope. The red curve represents the prediction equation, and the grey area ±3 SD of the training set. The dashed lines represent the test subjects.

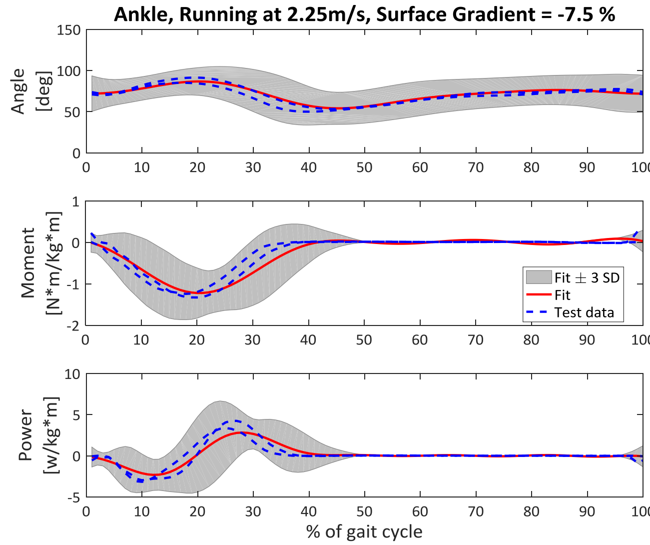

Figure 2: Test of the predictions using new slopes of -7.5% slope. The red curve represents the fit, and the grey area ±3 SD. The dashed lines represent test data.

CONCLUSIONS

The prediction equations enable predicting the leg joint angle, torque, and power during running as functions of the slope and percentage in the gait cycle. This set of equations could be used to gain a better understanding of locomotion, and may be helpful in the development of assistive devices such as prostheses and wearable robots.

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