TELESCOPING ACTION IMPROVES THE FIDELITY OF AN INVERTED PENDULUM MODEL IN NORMAL HUMAN GAIT

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INTRODUCTION

Inverted pendulum models, operationalized in ballistic walking studies [1] and passive dynamic robots [2], have been used to describe normal gait in the absence of active mechanisms, leading some clinicians to minimize the importance of joint powers [3]. We hypothesized that a telescoping action, associated with joint powers, would improve the fidelity of a simple inverted pendulum model applied to normal gait, as measured by its ability to predict horizontal and vertical ground reaction forces (*Fh*, *Fv*, respectively). Unlike previous studies, we made direct comparisons between model predictions and actual gait data for a sample of normal subjects.

METHODS

Kinematic data were collected for 24 normal children at 120 Hz using a ten camera Vicon 612 system, and low-pass filtered (6 Hz cutoff). A thirteen-segment, full-body model was implemented in Visual3D (C-Motion Inc.), and the instantaneous location of the full-body center-of-mass (COM) was calculated. *Fh* and *Fv* were collected at 1560 Hz using three AMTI force plates, and center-of-pressure (COP) coordinates were averaged, consistent with Eqs. (1) and (2) derived for a stationary pendulum pivot. (Here, m is body mass, g is gravitational acceleration, r is pendulum length, and θ, ω, α are the pendulum angular position, velocity, and acceleration, respectively.) Subtracting coordinates of the average COP from those of the instantaneous COM provided a telescoping inverted pendulum. Radial and angular kinematics of this pendulum were calculated using central difference techniques, and input to Eqs. (1) and (2), valid only for single support. Setting radial kinematics ($\dot{r}$, $\ddot{r}$) to zero removed the telescoping action. Inverse dynamics in Visual3D provided associated lower extremity joint powers. Five separate repeated measures ANOVAs detected differences ($p \leq 0.05$) among measured and predicted kinetic parameters (minima and maxima in *Fh* and *Fv*), with and without telescoping. Root mean square (RMS) errors were also calculated across ensemble averages to quantify differences between actual and predicted *Fh* and *Fv*.

$$Fh = m\left[\left(\ddot{r} - r\omega^2\right)\cos\theta - \left(r\alpha + 2\dot{r}\omega\right)\sin\theta\right] \quad (1)$$

$$Fv = m\left[\left(\ddot{r} - r\omega^2\right)\sin\theta + \left(r\alpha + 2\dot{r}\omega\right)\cos\theta\right] + mg \quad (2)$$

RESULTS AND DISCUSSION

Pendulum compression averaged 1.7 cm over the first 20% of single support, length changes were variable at mid single support, and extension occurred over the last 20% of single support. Ground reaction forces were predicted best when this telescoping action was included (Figure). RMS errors for *Fh* increased from 2.1%BW to 8.0%BW when telescoping was removed, as the predicted force diverged from actual values in early and late single support. RMS errors for *Fv* increased from 6.8%BW to 22%BW, and the double peak pattern was lost, when telescoping was removed. Peaks in *Fh* and *Fv* were significantly different for all comparisons (actual vs. telescoping, actual vs. no telescoping, telescoping vs. no telescoping), but this was not true for a local minimum in *Fv* near 50% single support. In every case, deviations from actual data were worse when telescoping was removed, and these deviations were greatest during lower extremity power bursts calculated for these subjects. We conclude that telescoping contributes to *Fh* and *Fv* during single support, and reflects changes in hip, knee, and ankle angles modulated by joint powers. We expect these findings to be amplified in a companion study of pathological gait, now underway. We also plan to explore correlations between radial powers ($F \cdot \dot{r}$) and joint power bursts.

REFERENCES

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2. McGeer T. *International Journal of Robotics Research* **9**, 62-82, 1990.
3. Perry J. *Gait Analysis*, p. 31, SLACK, Thorofare NJ, 1992.

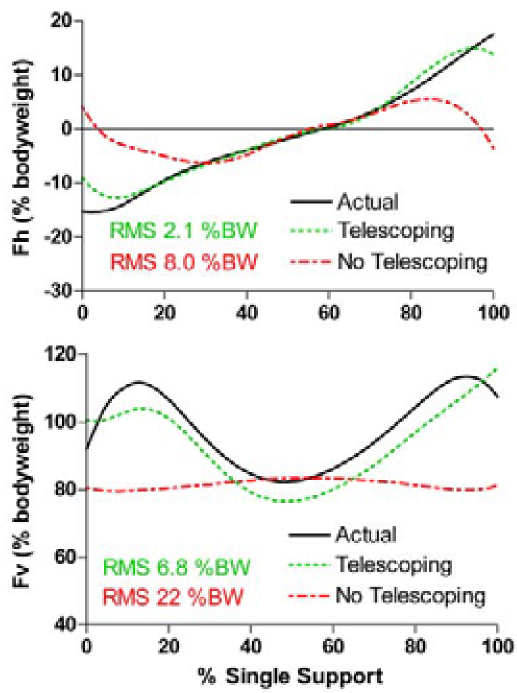

Figure: **Ensemble averages for actual and predicted *Fh* and *Fv*, with and without telescoping action (n = 24).** Note that peaks are attenuated without telescoping. (Standard deviation bands have been omitted for clarity.)