Analysis of Step Mechanics with Step Length Variation

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1 Introduction

Human walking gait mechanics can often be explained through minimization of an energetic cost function. When the optimal step length is forced to change, however, different strategies will undoubtedly be applicable. Humans or bipedal robots may be forced to take different step lengths when adapting to external constraints such as in obstacle avoidance or isolated foothold availability, or in stepping for balance recovery. This study compared parameters from normal step length to those from increasing step lengths to the point of step failure. The ultimate goal is to understand the human control principles that underlie motion at sub-optimal step lengths and the similar problems that must be solved in legged robotics.

2 Methods

Data was collected from twenty subjects, ten female and ten male, 18-25 years old. Informed consent was obtained and the procedure was approved by the university Institutional Review Board. Subjects first performed an uninformed, relaxed walking motion, which was used to determine normal step length. Next, forty-eight reflective markers were placed on the subjects at joint locations and other significant landmarks, and disposable surface bipolar electrodes were attached over lower-limb muscles.

Subjects began testing in a statically-balanced stance position with front and back foot each in contact with a forceplate and separated by the measured normal step length. They completed the step by bringing the back foot level with and alongside the front foot. Six motion analysis cameras (Vicon Motion Systems) recorded marker positions and two force plates (AMTI) recorded ground forces and moments in three directions. EMG electrodes recorded data from the medial gastrocnemius, tibialis anterior, vastus lateralis, and biceps femoris muscles on both legs. After three trials each at right and left foot forward, the front force plate was moved forward to increase the step length by 10% of body height and the trials repeated. Step length was increased until subjects were no longer able to complete the motion. One step at foot separation 0.5m was also recorded for all subjects.

Vicon C3D files of marker positions and ground reactions were analyzed with a custom MATLAB program (adapted from [2]) to create input files for the OpenSim musculoskeletal analysis program (simtk.org; [1]). A full-body musculoskeletal model with 23 degrees-of-freedom in the lower extremities (gait2354) was scaled to each subject and marker positions on the model moved to match subject marker positions.

Each step motion was reproduced in the OpenSim Inverse Kinematics procedure by computing for each frame the coordinate position of the model in a pose that best matched the recorded marker positions by weighted least-squares criteria (Fig. 1). The Inverse Dynamics procedure then used the motion of the model to solve the equations of motion for the multibody system for the unknown generalized joint reactions. Results from the three right-foot-forward trials at each step length were averaged for each subject and normalized by the subject's mass in kg. Means at each step length were then averaged across nine female subjects. Steps were labeled as 0: 0.5m step; 1: normal step length; 2, 3, 4, 5: normal step length plus 10% height succesively. Subjects successfully completed step 3 (n=1), 4 (n=3), or 5 (n=5).

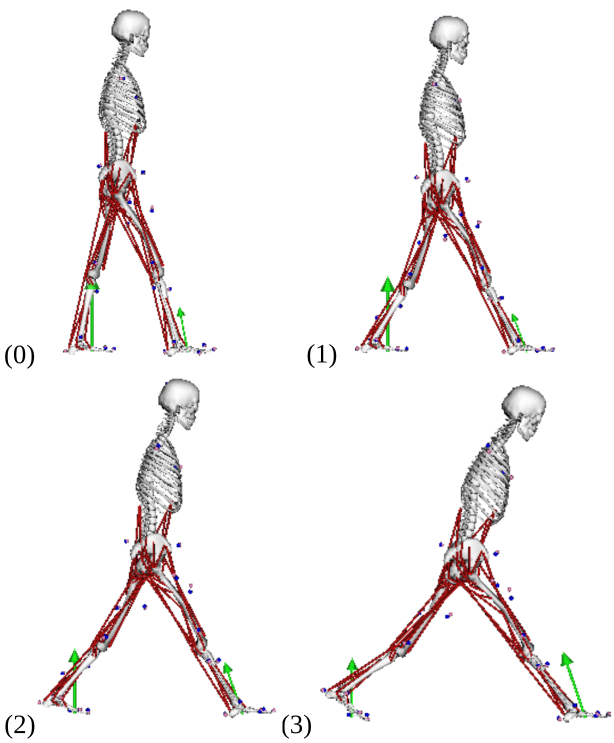

Figure 1. OpenSim models showing subject position at the beginning of a right-foot-forward step for steps 0,1,2,and 3. Green arrows show center of pressure and the direction and magnitude of the ground reaction force.

3 Results

Back hip moment peaked in flexion before toe-off and then declined to zero except for a small negative rocking as the subject straightened (Fig. 2). Front hip moment was extensional with a variable swing (absent entirely in some subjects) as the subject shifted weight to the front leg. The peak occurred just before back toe-off. The mean peak back hip moment was greater than the front, and both increased monotonically with step length (Fig. 3a).

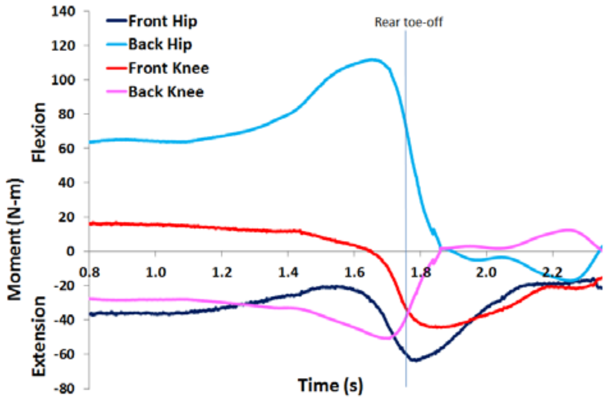

Figure 2. Typical moments from a single trial. Time is truncated when the rear foot begins weight-bearing on the front force plate.

Knee moments were of lesser magnitude than hip moments, with the peak back knee moment larger than the front (Fig. 3b). The back knee moment began in extension and increased in magnitude to peak just after the peak in back hip moment (Fig. 1). The front knee moment began in flexion but became more positive throughout the step motion to peak in extension after toe-off as the subject's body shifted to the front. Mean maximum knee moments increased monotonically with step length (Fig. 3b).

Ankle moments were the most variable among subjects, particularly in the front leg. Both front and back ankle moments were in the plantarflexion direction and fairly constant across step lengths, the back ankle moment being approximately twice as large as that of the front (-0.90 vs -0.45 N-m/kg; Fig. 3c).

4 Future Work

The results to date only involve one-half of the subject pool; the males are not yet included. A static optimization procedure in OpenSim will also be performed on all models. This uses the positions, velocities, and accelerations of the model as matched to the subject motion to solve the equations of motion for unknown generalized forces constrained by the muscle force-length-velocity properties while muscle activation level is globally minimized. Results will be compared to the actual EMG recordings.

References

[1] Delp SL, et al. OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement. *IEEE Trans Biomed Engr 54(11):*1940-1950, 2007.

[2] Kelly, John. An Investigation and Expansion of Musculoskeletal Modeling and Analysis Techniques. Master's Thesis, North Carolina State University, 2008.

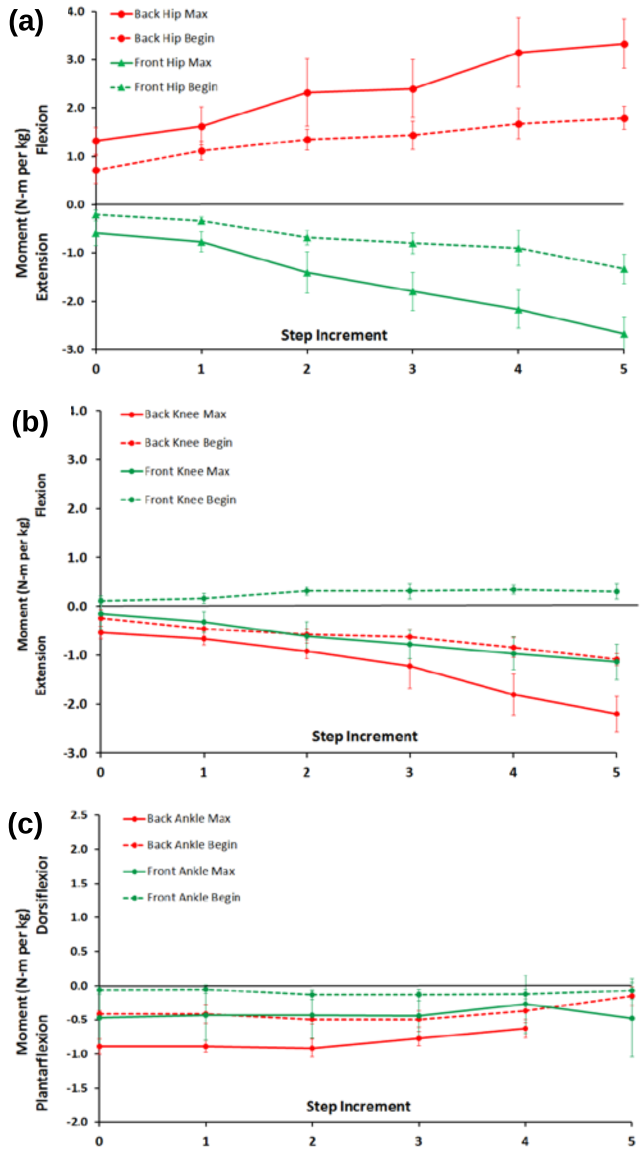

Figure 3. Maximum and beginning joint moments as a function of step increment (mean ± SD, n=9). (a) Hip; (b) Knee; (c) Ankle. All moments shown positive in flexion.

5 Open Questions

- What other variables are of interest, either for human gait analysis or for the robotics community? Some examples are joint forces, center-of-pressure location, body center-of-mass location, and individual muscle forces.
- Should the beginning moments be used to adjust the maximum moments?
- Is there a change in strategy as step length increases?
- What basic principles can be extracted from these results?