HUMAN POSTURAL MODEL THAT CAPTURES ROTATIONAL INERTIA

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INTRODUCTION

Inverted pendulum models have been very beneficial for the modeling and analysis of human gait and balance [Kuo, 2007]. These reduced models allow us to ignore the movements of the individual limbs, and instead, focus on two important points -- the center of pressure (CoP) and the center of mass (CoM) -- and the *lean line* that connects the two points. A limitation of the existing reduced models is that they represent the entire human body only as a point mass and do not characterize its moment of inertia. The rotational inertia is a property of the distributed masses of the limbs, and by ignoring it, un-natural constraints, such as zero angular momentum at the CoM and resultant ground reaction force (GRF) collinear with the lean line, are forced on to the model.

The Reaction Mass Pendulum (RMP) model [Lee & Goswami, 2007] extends the existing models by replacing the point mass with an extended rigid body – the abstracted 3D reaction mass – that characterizes the aggregate rotational inertia of the subject projected at the CoM. As the person moves through different limb configurations, the centroidal moment of inertia continuously changes, which is captured by the changing shape, size and orientation of the ellipsoidal reaction mass. We postulate that analysis of the rotational inertia especially in cases of pathological gait can provide additional insight. This is demonstrated with normative gait data from four able-bodied subjects and pathological gait data from one spinal cord injured subject.

METHODS

The incomplete spinal cord injured subject (ISCI) was a 34 years old male (weight: 66 Kgs, height: 1.68 m) with T1 motor incomplete spinal cord injury (ASIA D) that resulted in left hemiplegia, who could walk only short distances with rolling walker. Four able-bodied volunteers (age: 39.25±15.9 years, weight: 68±9 Kgs, height: 1.59±12 m), who had no known injury or pathology during the study. Informed consent was obtained from the subjects before their participation.

Retro-reflective markers were placed on the body segments according to the 'plug-in' gait marker set in the Vicon Workstation (Vicon Peak, USA) software to acquire lower-body kinematics data using a seven camera Vicon motion capture system. Two multi-axis force platforms (AMTI, USA) were embedded in the floor of the walkway. The subjects learned to step on the first force platform with their left foot and then step on the second force platform with their right foot after taking three over-ground strides at their preferred speed. The gait data was analyzed with custom software developed in Matlab (The Mathworks, USA). We projected the time-course of segmental CoM position and segmental orientation of thorax, pelvis, bilateral femur, bilateral tibia, and bilateral foot from both able-bodied and ISCI subjects on to an RMP model. All mass and length variables were normalized using subject's body mass and height, respectively.

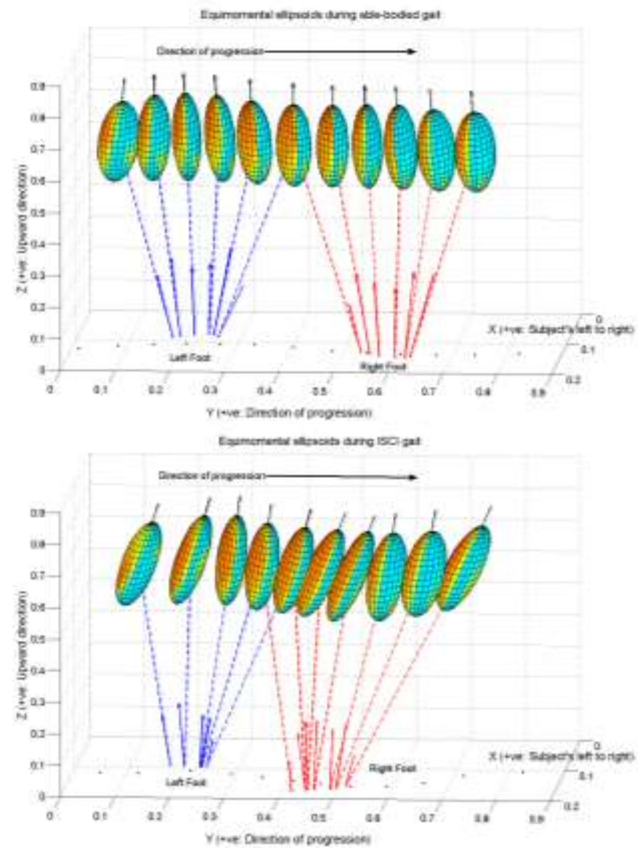

Figure 1: The figures show the evolution of RMP for able-bodied (top panel) and ISCI gait (bottom panel).

Figure 1 shows successive snapshots of the evolution of the RMP model of human gait. At each snapshot the resultant GRF is shown by an arrow originating from the CoP on force platform, with blue arrow showing the left foot and red arrow showing the right foot GRF. Also shown are the corresponding lean line (in dashed) and the 3D inertia ellipsoid. The RMP model was constructed as follows: at every instant the inertia matrix of each body segment was computed using anthropometric data [de Leva, 1996] and was projected to the aggregate body CoM using the corresponding spatial transformation matrix. All the projected segmental inertia matrices were summed to obtain the centroidal composite rigid body inertia (CCRBI) matrix. The semi-axes of the inertia ellipsoid were computed from the eigenvalues of CCRBI matrix while the orientation was given by its eigenvectors.

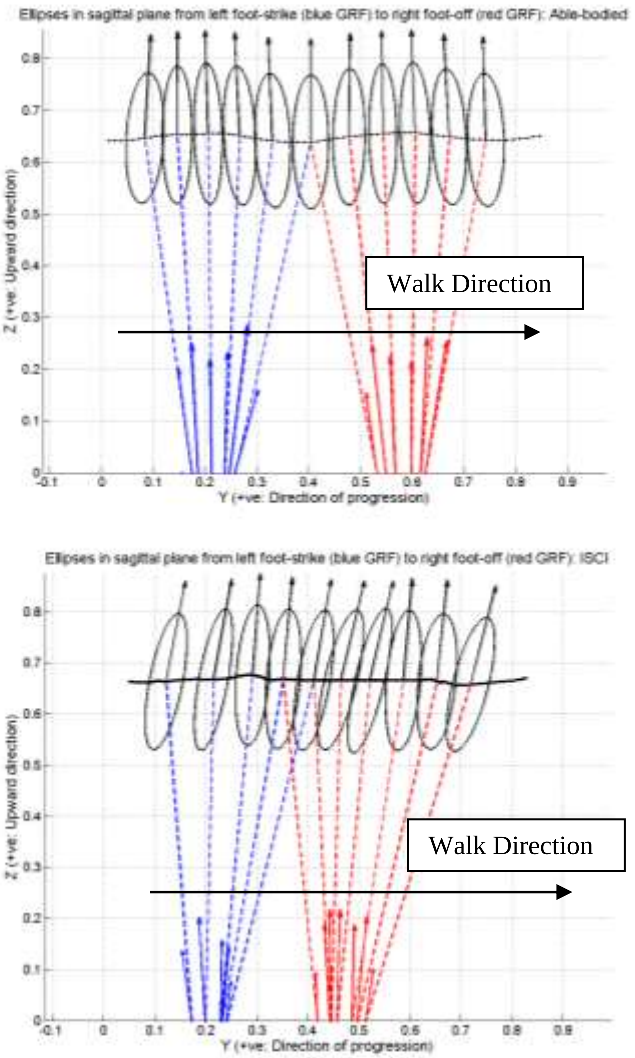

Figure 2: The figures show the evolution of RMP in sagittal plane for able-bodied (top panel) and ISCI gait (bottom panel).

RESULTS AND DISCUSSION

We analyzed the evolution of the RMP model in sagittal plane for able-bodied as well as ISCI gait. Figure 2 shows the GRF from the left-foot (blue) and right-foot (red), the lean line, inertia ellipses in sagittal plane, their centroids (i.e., CoM trajectory) and their orientation. Figure 2 clearly shows that the resultant GRF is not always collinear with the lean line, especially in the case of ISCI gait. This creates a Centroidal Moment (CM) about the CoM, as shown in Figure 3, row 3. Note that traditional point mass pendulum models will incorrectly force the collinearity of the GRF and lean line, and will indicate a zero CM. The heel-strike and foot-off were lined up over multiple trials (able-bodied: 40 trials, ISCI: 10 trials) for ensemble averaging. Time abscissa was normalized by the duration from left heel-strike to right foot-off.

Figure 2 shows a flatter CoM trajectory and a consistent forward tilt of inertia ellipse for ISCI's forward-flexed walker-aided gait when compared to able-bodied gait. Figure 3, row 1 shows that both gaits have similar pattern of the inertia ellipse shape and size. However the ISIC gait has a more pronounced vertical tilt in the sagittal plane (Figure 3, row 2). Figure 3 shows that the Centroidal Moment (CM) mostly counteracted the tilt of the ellipse in able-bodied gait except just prior to and during DS phase (tilt almost zero) while it is more complex for ISCI gait.

The cost of pendular gait is largely focused on DS phase i.e., the step-to-step transition work, which may account for 60-70% of the overall metabolic cost [Donelan et al., 2002]. Point-mass pendulum models underestimate energy cost and favor shorter and faster steps in absence of rotational inertia [Kuo, 2007], which is accounted for in the RMP model.

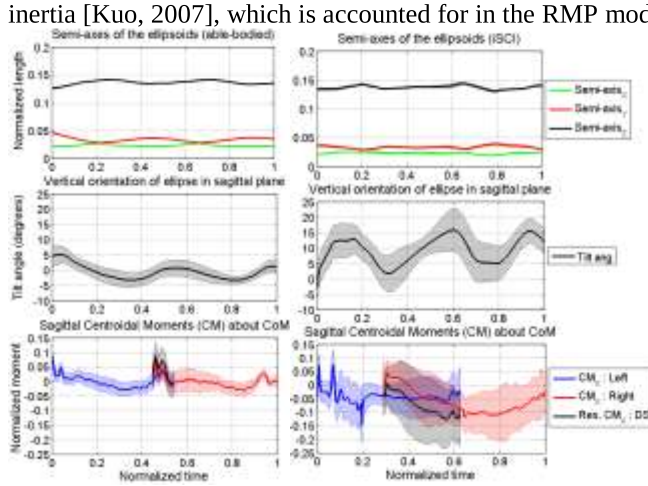

Figure 3: The figures show the semiaxes of inertia ellipsoid (first row), their sagittal plane orientation (second row: anterior tilt +ve) and the centroidal moment (CM) in sagittal plane (third row) for able-bodied (left panels) and ISCI gait (right panels). DS: double-support phase of gait.

SUMMARY

1. RMP model augments the traditional point-mass pendulum model by capturing the shape, size and orientation of the aggregate rotational centroidal inertia.
2. RMP model captures the natural centroidal moment created by the GRF about the CoM. This needs further investigation for ISCI (pathological) gaits.

REFERENCES

Kuo, A. D. (2007). *Human Movement Science*, 26, 617-656.
Lee, S. H. and Goswami, A. (2007). *Proceedings of ICRA07*, 4667-4672.
De Leva, P. (1996). *J Biomech.*, 29(9), 1223-1230.
Donelan, J. M., Kram, R., and Kuo, A. D. (2002). *Journal of Experimental Biology*, 205, 3717-3727.

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