# Estimation of Center of Mass Displacement based on Gait Analysis

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## Introduction

➢ Motion capture (Mocap) has been applied extensively in education, training, sports, and recently computer animation for television, cinema and video games.
➢ Locomotion is the fundamental skill of human beings, and many forms of locomotion, like walking, running, jumping and climbing are being studied and used in computer animation.
➢ Different from the vision-based Mocap, data capture and processing in Micro-sensor Mocap (MMocap) are mainly done in the sensor coordinate system and the subject's body coordinate system. There is no information about the subject's movements with reference to the global coordinate system, which is important for many applications.
➢ This study proposed a method to estimate the Center of Mass (CoM) displacement to reconstruct the human locomotion in the global coordinate system.

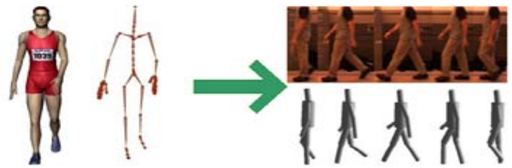

Fig. 1 - Posture and Locomotion

## System Prototype

**Our prototype system consists of three parts:**

➢ ***Sensor subsystem:*** includes 16-20 micro-sensor nodes (each node contains a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer) and a base station connected by a data bus. Sensor nodes are placed on the segments of the human body (head, shoulders, spine, upper and lower limbs) to collect the motion data. The base station controls the data sampling rate range from 50Hz-200Hz. It also sends data packets via USB or high-speed wireless module to the CPU for data processing by the data fusion and animation subsystems;
➢ ***Data fusion subsystem:*** fuses sensory data and biomechanical constraints to get the orientation information using Multi-model Kalman Filter under Bayesian network theory and obtain the locomotion information by gait analysis;
➢ ***Animation subsystem:*** uses the orientations and locomotion information to reconstruct the movements onto a 3D avatar model.

In this project, a subject wearing the sensor nodes performs a set of actions, while the 3D avatar reconstructs the movements in real-time.

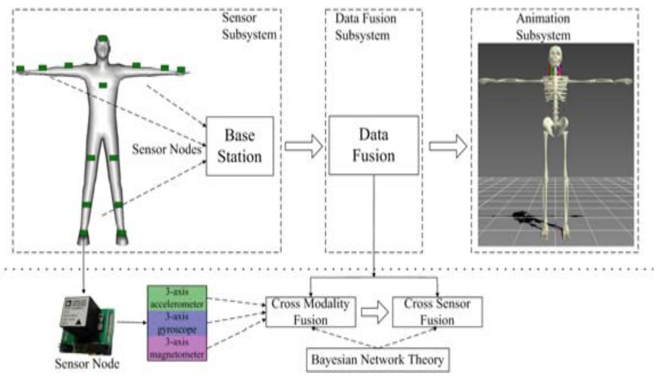


Fig. 2 - Mocap system prototype

## Methods

### 1. Gait event detection

- Each gait cycle is divided into two phases: stance phase, starting by a Heel-Strike (HS) and swing phase, starting by Toe-Off (TO).
- During the stance phase, the squared Euclidean norm of the acceleration measurements of the feet should be close to the gravitational acceleration.

$$TH_2 < \left\|\tilde{a}_{x,t} + \tilde{a}_{y,t} + \tilde{a}_{z,t}\right\|^2 < TH_1 \quad (1)$$

- A time heuristic algorithm must be applied to the squared norm of acceleration data to detect the stance phase properly.

### 2. Segmental kinematics transmission

- The human lower body is modeled as a kinematic chain of seven rigid segments linked by joints, i.e. hips, knees, ankles and toes.
- We build two sets of the lower body segments, namely, $S_L$={Pelvis, Lfemur, Ltibia, Lfoot} and $S_R$={Pelvis, Rfemur, Rtibia, Rfoot}, and also two sets of the joints $J_L$={Pelvis, Lhip, Lknee, Lankle, Ltoe} and $J_R$={Pelvis, Rhip, Rknee, Rankle, Rtoe}.
- From the proximal joint, e.g. root joint, to the distal joint, the position of the child joint can be calculated from its parent joint's position:

$$p_{J_R(k),t} = p_{J_R(k-1),t} + q_{S_R(i),t} \otimes V_{S_R(i),0} \otimes q^{-1}_{S_R(i),t} \quad (2)$$

where $i$ = 1, 2, 3, 4 and $k$ = 2, 3, 4, 5.

- From the distal joint, e.g. right toe, to the proximal joint, the position of the parent joint can be calculated from its child joint's position:

$$p_{J_R(k-1),t} = p_{J_R(k),t} - q_{S_R(i),t} \otimes V_{S_R(i),0} \otimes q^{-1}_{S_R(i),t} \quad (3)$$

where $i$ = 4, 3, 2, 1 and $k$ = 5, 4, 3, 2.

### 3. Estimation of Center of Mass (CoM) displacement

- During walking, the root joint is considered as the CoM of the human body. To estimate the CoM displacement, we need to first determine which joint is the reference joint for kinematic transmission during walking.
- When the right leg is selected as the support leg, the position of the right toe joint is considered as the reference position:

$$p_{Ref,t} = p_{J_R(5),t} \quad (4)$$

- The positions of other joints, namely, right knee, right hip, root joint, left hip, left knee, left ankle, and left toe can be obtained in turn relative to the reference position.
- When the left leg is the support leg, the reference joint changes to the left toe, the position of the left toe at the previous time slice t-1 is considered as the reference position:

$$p_{Ref,t} = p_{J_L(5),t-1} \quad (5)$$

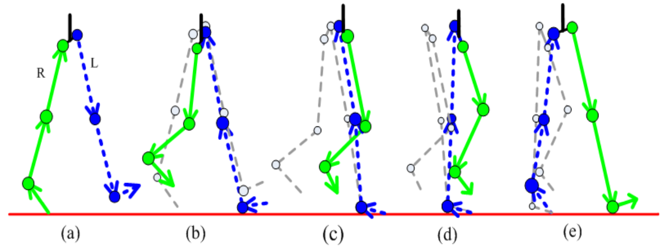


Fig. 3 - The stick model of the walking gait. (a): Left terminal swing, Right terminal stance, Right toe reference. (b), (c), (d): Left support leg, Left toe reference. (e): Left terminal stance, Right terminal swing, Left toe reference. The grey dash lines represent the lower body movements of the last figure.

## Results

### 1. Verified by Simulated Sensor data

Use the motion data from the CMU Mocap database. From the root position and relative orientation data, the position, velocity, acceleration, orientation, and angular velocity of each model joint can be calculated.

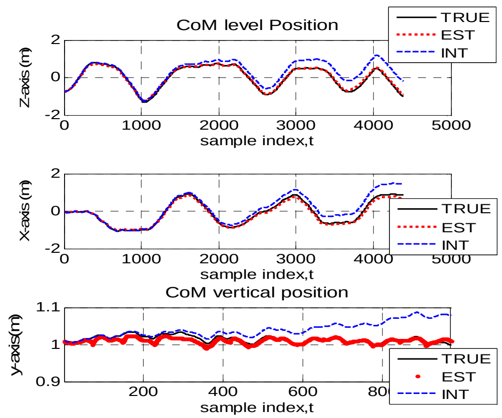


Fig. 4 - The CoM level position of forward, backward, and sideways walking (CMU Subject 41 trial 2) (Z: upper; X: middle; Y: lower). INT: Integration of the acceleration data from the pelvis; EST: Our proposed method; TRUE: The ground truth. The sampling rate is 120Hz.

### 2. Experimental results from our MMoCap system

The performance of our algorithm is evaluated by the walking experiments in which the subject walks forward from point (0,0) to (3,2), then sideways from (3,2) to (5,0), backward from (5,0) to (2,-2) and finally sideways from (2,-2) to (0,0). The experimental results are given in Fig. 5. The level trajectory shown in the upper figure is consistent with the ground truth.

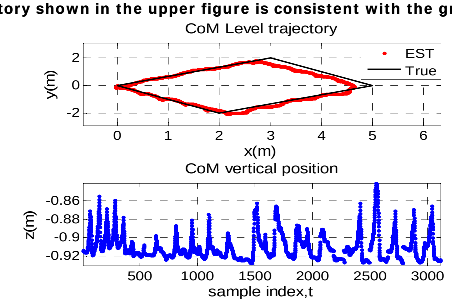


Fig. 5 - Walking displacements captured by our MMoCap system. The sampling rate is 100Hz.

## Conclusion

This study proposes a novel method to estimate the CoM displacement during walking based on gait analysis and kinematics. The method allows continuous estimation of CoM movements by merely wearing seven SMUs on the human lower body segments. Our MMocap system is highly portable, which opens up many possibilities for applications of this system in daily life as an effective and quantitative gait analysis tool.
Our future work is to estimate other types of locomotion where both feet leave the ground, like running and jumping.

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