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Fusion Integration: COM Trajectory From a Force Platform

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A fusion integration algorithm is used to estimate the one-dimensional center of mass (COM) trajectory from force platform data. The resulting COM trajectory combines the best attributes of several established algorithms used to estimate the COM trajectory, and it appears to have the advantage of being robust, accurate, continuous in its higher derivatives, and fast to obtain. In current research projects, variations of the fusion integration algorithm have been adapted by the authors for the analysis of postural balance and the sensing of limb orientations with inertial measurement units.

Key Words: fusion, center of pressure, optimization, and postural balance

A considerable amount of research has been completed on how humans maintain postural balance, but no single explanation is universally accepted. Further understanding will be facilitated by the ability to obtain an accurate and continuous estimate of the whole body center of mass (COM) trajectory and higher derivatives from force platform data. Several research papers have suggested COM velocity and jerk as possible control variables in the coordination of skilled human movement (Masani et al., 2006; Yan et al., 2000), and, unlike COM location, it is feasible they could be measured by biological sensors such as the Golgi tendon organs.

Several methods have been used to estimate the COM trajectory during quiet standing. Each method cited is useful and has unique advantages. However, no one method is able to able to provide a complete picture. Methods include the kinematic method (Lafond et al., 2004), the center of pressure (COP) low-pass filter method (Caron et al., 1997; Brenda et al., 1994), the zero-point-to-zero-point double integration algorithm (Zatsiorsky et al., 2000), the iterative model (Levin & Mizrahi, 1996), and the dynamic method (Shimba, 1984).

The kinematic method produces a continuous and accurate trajectory of absolute gross COM movement. Measured kinematics of body segment markers and inertial models are used to estimate COM position. However, measurement noise such as that from skin artifacts may obscure high-frequency postural adaptation to small perturbations. The COP low-pass filter method also results in a continuous COM trajectory. It is based on the observation that low-pass filtering of the COP trajectory can approximate the COM trajectory. It can be obtained with minimal computation and is a good first approximation for quiet standing applications. Unfortunately, by the very nature of the method, high-frequency information is discarded.

Recent improvements in computing power have facilitated the use of more complex algorithms, such

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as the zero-point-to-zero-point double integration algorithm, which uses successive zero-crossings in the horizontal force to make discrete corrections to the COM trajectory estimated by the double integration of horizontal acceleration. The high-frequency content of postural sway is preserved but discontinuities in the COM velocity and higher derivatives are introduced .

The dynamic method and the iterative model use equations similar to the fusion integration algorithm presented in this article to estimate COM trajectory. However, without using iteration, the dynamic method is unable to solve the derived equations and thus the equations are simplified, resulting in the COP becoming a second estimate of the COM. The iterative model uses iteration to optimize the initial position and velocity of the COM trajectory. Raw data are band-pass filtered between 0.25 and 4 Hz to reduce accumulated integral error and high-frequency noise, which results in some loss of information. In quiet standing, the COM trajectory contains low-frequency "ramble" (Zatsiorsky & Duarte, 2000), and thus some of the ramble component will be lost with a 0.25-Hz low cutoff.

The fusion integration algorithm presented here provides an accurate trajectory of the COM, continuous in all derivatives, by drawing on the best aspects of the five algorithms previously described. Variations of fusion integration may be useful for estimating other parameters where accurate post-processing estimates are more desirable than real-time Kalman filter estimates, for example in GPS surveying and measurement of limb movement by inertial measurement units.

Methods

Fusion Integration Overview

Error is inherent in all measurements. The purpose of the fusion integration algorithm is to obtain an accurate estimation of COM trajectory from force platform measurements; this is COM_{Fused} (Figure 1). COM trajectory can be estimated by integration of horizontal ground reaction forces ($COM_{Integrate}$) and by Newton–Euler methods (COM_{Torque}), both of which contain calculation error. Knowledge of the nature of the calculation error is used in the fusion process to obtain COM_{Fused}. The process is iterated until convergence between the various solutions is reached. Iteration includes estimation of the measurement error based on COM_{Fused}, the force platform data, and an appropriate error model.

Derivation of the Mechanical Equations

Two complementary estimates of the COM trajectory are possible. $COM_{Integrate}$ is the double integral of horizontal ground reaction forces with the integration constants (K1, K2) chosen to best match the COP data (Equations 1–3):

$$K1 = COP_{t=0} \tag{1}$$

$$K2 = \frac{COP_{t=end} - COM_{t=end}}{Time} \tag{2}$$

$$COM_{Integrate} = \iint \frac{Fx}{m} dt + \int K2 dt + K1 \tag{3}$$

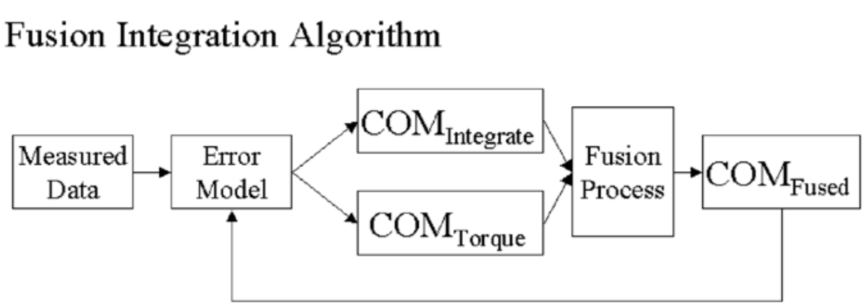

Figure 1 — Fusion integration algorithm. Two estimates of COM trajectory, COM_{Torque} and $COM_{Integrate}$ are derived from force platform data. The estimates are fused and the result, COM_{Fused}, is used for subsequent iterations until convergence is reached.

COM_{Torque}, Equation 9, is derived from Euler's equation applied to a polar coordinate description of the motion that could be considered similar to the single link inverted pendulum model already validated by Winter (1995). However, the model is relaxed to allow horizontal forces to be independent of vertical forces, thus allowing multi-link body sway. The COM location is represented in polar coordinates by an angle (θ) and a pendulum length (r). The mechanical equations can be derived for the relaxed inverted pendulum over the range $-\pi/2 < \theta < \pi/2$ (Figure 2) and are primarily designed to compute a noisy estimate of COM_{Torque}.

$$\theta = \arcsin\left(\frac{-COM}{r}\right) \quad and, \quad r\sin\theta = -COM \tag{4}$$

$$\alpha = \frac{d^2\theta}{dt^2} \tag{5}$$

$$COP = {Mz}/{Fy} - mean({Mz}/{Fy}) \tag{6}$$

The origin of rotation (O) is arbitrary, but to reduce the range of θ and r, it is assigned to the mean COP position at ground level. Within the range of movement in quiet standing, the pendulum length, r(t), is assumed to vary only slightly about a mean value taken as 56.4% of subject height (Zatsiorsky, 2002). Therefore, if (r) is fixed at the estimated mean value, the complexity of the problem can be greatly reduced, but the model is now accurate in only one dimension along the horizontal axis and systematic noise is introduced to the final COM_{Torque} estimate especially if r changes significantly. Euler's equation and data from the force platform allow calculation of the sum of moments about the arbitrary origin, Equations 7 and 8, from which an instantaneous COM_{Torque} position can be estimated, Equation 9. COM_{Torque} is based on the second derivative of θ, which is noisy, and an estimation of moment of inertia (I), which may be inaccurate; however, over enough data points, it is assumed that COM_{Torque} is normally distributed about the true COM trajectory.

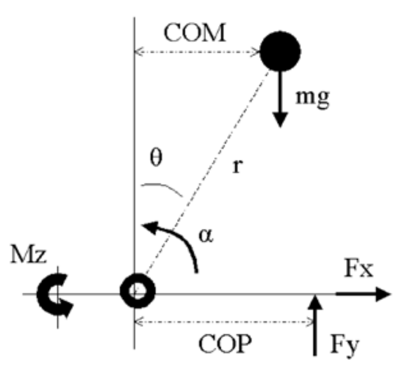

Figure 2 — A free-body diagram of a subject standing on a force platform. The complex multilink motion is simplified to an instantaneous COM location described by radial length (r) and angular position (θ). Fx, Fy, and Mz are the forces and moment measured by the force platform in the xy-plane.

$$\sum T = I\alpha \quad and \quad I = mr^2 \tag{7}$$

$$\sum T = COP * Fy - COM * mg \tag{8}$$

$$COM_{Torque} = COP\frac{Fy}{mg} + \frac{I\alpha}{mg} \tag{9}$$

The Fusion Process

Of the two complementary estimations of the COM trajectory available for fusion, COM_{Torque} is noisy but its mean value is accurate in the long term (this could be termed *low-frequency accuracy*), whereas $COM_{Integrate}$ is accurate in the short term but suffers accumulated integration error (this could be termed *high-frequency accuracy*). By fusing the two complementary estimates to obtain COM_{Fused} a more accurate and continuous estimate of the COM trajectory is possible. COM_{Fused} is simply the high-frequency component of $COM_{Integrate}$ plus the low-frequency component of COM_{Torque}.

The error between the two COM estimates is calculated with Equation 10. $COM_{Correction}$ is obtained by filtering the noisy error signal with a bidirectional 2nd-order low-pass Butterworth filter, Equation 11.

$$COM_{Error} = COM_{Torque} - COM_{Integrate} \tag{10}$$

$$COM_{Correction} = lowpass\_filter\left(COM_{Error}\right) \tag{11}$$

$COM_{Correction}$ relies on the assumption that COM_{Error} is normally distributed about the true integration error. A cut-off frequency of 0.5 Hz was found to exclude most systematic error and allow convergence to a solution.

The continuous estimation of COM trajectory, COM_{Fused}, is calculated by adding the estimated correction for integration drift to the raw integration estimate, Equation 12.

$$COM_{Fused} = COM_{Integrate} + COM_{Correction} \qquad (12)$$

The Iterative Process

The accuracy of COM_{Fused} can be improved with iteration. The fusion integration sequence of equations is circular because the estimate of COM_{Torque} depends on the estimated angular acceleration (α), but α depends on angular position (θ), and θ depends on COM_{Fused}, which in turn depends on the COM_{Torque} estimate (see the feedback loop, in Figure 1). The first iteration assumes that COM_{Torque} is equal to COP; subsequent iterations use the previous COM_{Fused} estimate. Convergence is reached when the resulting COM_{Fused} trajectory does not change in successive iterations; typically, this takes fewer than 10 iterations.

In addition, the second derivative of COM_{Fused} is an estimate of the "true" horizontal force. In each iteration, the "true" and measured forces are used to fit parameters to an error model. The measured horizontal force data are then corrected by the measurement error estimates (Figure 1). The error model can be as simple as a zero bias, or as complex as a model describing the dynamics of platform deformation with loading.

Experimentation

A single healthy male subject—age 32 years and height 1.76 m—volunteered to complete the Fall Risk test three times in 1 day. The Fall Risk protocol consists of six test conditions (Brodie & Walmsley, 2005). The raw force platform data from these 18 measurements were collected for 10 s at a 50-Hz sample rate and processed with the fusion integration algorithm, the zero-point-to-zero-point algorithm, and the COP low-pass filter algorithm with a 0.5-Hz cutoff.

In a separate Dynamic Sequence Test, a single subject was asked to complete the following sequence of stances while data were recorded for 20 s at 50 Hz: (1) bipedal, (2) right foot unipedal, (3) bipedal, (4) left foot unipedal, and (5) bipedal.

The data were collected on a portable AMTI Accugait force platform placed on a flat concrete floor covered with linoleum. All subjects gave informed consent as required by Massey University Human Ethics Committee (WGTN Protocol–04/38). The fusion integration algorithm, written in MATLAB, takes less than 1 s on a Pentium 2,733-MHz computer to process 10 s of data collected at 50 Hz. The fusion integration algorithm's MATLAB m-files are available from the authors.

Results

In quiet unipedal standing, the COM range of movement is small, approximately 13 mm (Figure 3). The COM trajectory as predicted by fusion integration, COM_{Fused} (smooth solid line), and the zero-point-to-zero-point algorithm estimation, COM_{ZP} (dashed line), are highly correlated as measured by the Pearson's correlation coefficient ($r^2 = 0.97$) (Table 1).

For a dynamic sequence of movements, the COM range of movement is larger, approximately 28 cm (Figure 4). The fusion integration prediction, COM_{Fused} (smooth solid line), appears to be more robust than the zero-point-to-zero-point algorithm estimation, COM_{ZP} (dashed line), which predicts a COM trajectory beyond the COP and base of support. In the dynamic sequence, the fusion algorithm is highly correlated with the COP low-pass filter method ($r^2 = 0.99$).

Discussion

Because the zero-point-to-zero-point algorithm has been shown to compare well with kinematic data (Lafond et al., 2004), the output from fusion integration was compared with that from the zero-point-to-zero-point algorithm (Figure 3). The COM trajectory from fusion integration (solid line) and

Table 1 Comparison by Correlation of the COM Trajectory Calculated by Three Methods

	Correlation coefficient, r^2		
	Fusion vs. zero point	**Fusion vs. COP low pass**	**Zero point vs. COP low pass**
Fusion (static trial)	0.97	0.96	0.92
Fusion (dynamic trial)	0.86	0.99	0.85

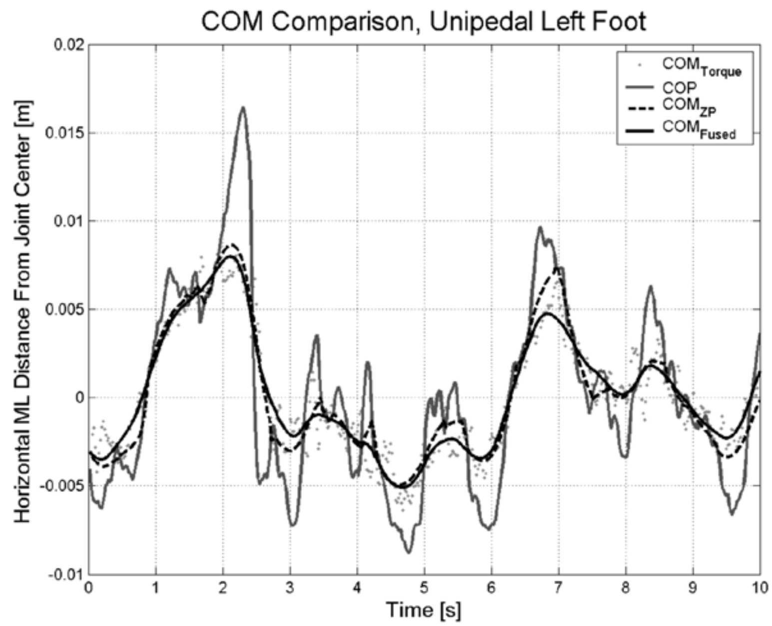

Figure 3 — Comparison of methods used to calculate COM trajectory from force platform data in quiet unipedal stance. The calculated COP is a reference. COM_{Torque}, the dots, is noisy. COM_{ZP} is the dashed line. COM_{Fused} is a continuous line that has both short-term and long-term accuracy.

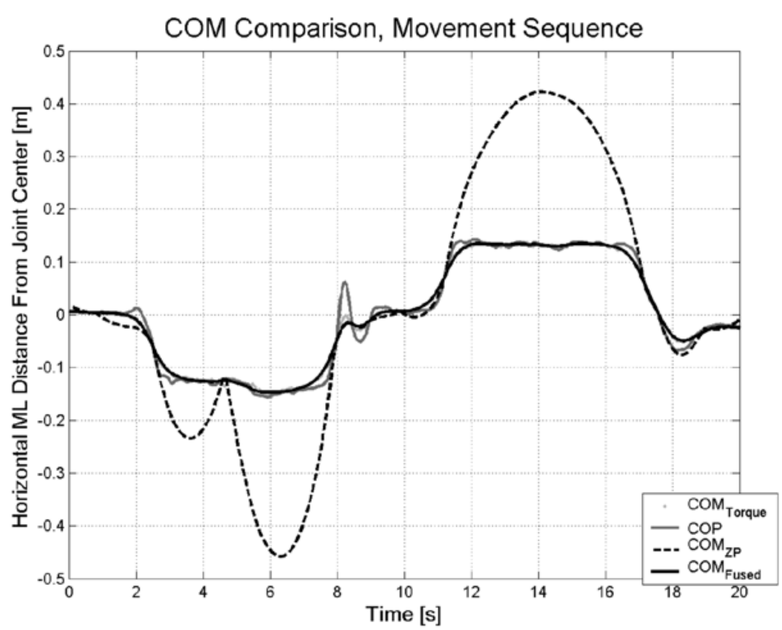

Figure 4 — Comparison of methods used to calculate COM trajectory from force platform data in a dynamic task. The COM_{Fused} estimate appears more robust than the COM_{ZP} estimate, as it remains within the base of support defined by the COP trajectory.

that from zero-point-to-zero-point (dashed line) are in excellent agreement in the quiet standing trial.

For a dynamic sequence of movements, the fusion integration estimation appears more robust than the zero-point-to-zero-point estimation (Figure 4). The fusion integration estimate (solid line) remained close to the COP trajectory, whereas the zero-point-to-zero-point estimation (dashed line) was unstable when the subject was not standing in the center of the force platform, and it predicted a COM trajectory beyond the COP base of support.

The instability of the zero-point-to-zero-point algorithm may be a result of slight platform tilt, less than 0.5°, arising from the compressibility of the linoleum floor and that has resulted in a changing proportion of the vertical reaction force being recorded in the horizontal force channels as the subject moved. The fusion integration algorithm is robust to this measurement error because it uses the complete data set to calculate COM_{Torque} and to estimate the integration drift error. From a signal processing perspective, this is more desirable than the use of intermittent zero points.

In conclusion, the fusion integration algorithm has successfully combined the best aspects of several established algorithms to produce a continuous and accurate estimate of COM trajectory for both quiet standing and dynamic tasks. Its use for such dynamic tasks as walking or jumping may require further development to produce a three-dimensional trajectory by including changes in radial COM location.

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