INTRODUCTION
Recent advances in MEMS accelerometers have allowed cost effective and reliable angular acceleration measurement using two accelerometers mounted at fixed separation distance [1-3]. The angular acceleration measurements were successfully used to estimate foot orientation in pedestrian navigation [2], and to estimate angular velocity of an electric motor using a Kalman filter [3].

The purpose of the current paper was to compare two methods for measurement of angular acceleration of the foot (accelerometer versus gyroscope) using a wearable inertial measurement unit (IMU) that incorporates two MEMS multi-axis inertial sensors.

METHODS
An IMU with two 6-axis digital inertial sensors (MPU6050, Invensense, Sunnyvale, CA) was designed and fabricated (Fig 1). Each sensor contained a 3-axis gyroscope and a 3-axis accelerometer as well as signal conditioners and simultaneous 16-bit analog to digital converters in approximately 5mm x 5mm package.

The range of gyroscopes (gyro) and accelerometers were set at ±1,000º/s and ±16g, resulting in resolutions of 0.03º/s and 0.0005g, respectively. Signal bandwidth was set at approximately 180 Hz, with internal sampling at 1000 Hz. The digital data from each sensor was recorded into onboard memory at 200 Hz after receiving a wireless trigger to synchronize with force plate data collection (Kistler, Amherst, NY).

Three normal walking trials of one male subject were collected after approval from the Institutional Review Board of the university. The IMU was secured to the dorsal surface of the shoe with a shoe lace (Fig 2). The subject walked approximately 10 steps on the walkway at a comfortable pace of approximately 1 Hz stepping frequency.

Data from the onboard memory was transferred to a PC to calculate angular acceleration about the medial-lateral axis by using Matlab (Natick, MA). Accelerometer- and gyro-based calculations were performed using two respective formulae:

\[ \alpha_{\text{accel},i} = \frac{a_{y1,i} - a_{y2,i}}{L} \]

\[ \alpha_{\text{gyro},i} = \frac{d\omega_z}{dt} = \frac{\omega_{i+1} - \omega_{i-1}}{2\Delta t} \]

\[ a_{y1} \] and \[ a_{y2} \] were the vertical accelerations from sensor #1 and #2, respectively, \( L \) (50.8 mm) was the distance between the sensors, and \( \omega_z \) was angular velocity about the medial-lateral axis measured by gyro. Three gyro-based angular accelerations were calculated for comparison purposes: sensor #1, sensor #2, and the average of the two. No data filtering other than DC offset removal was performed.
RESULTS AND DISCUSSION
Excellent agreement among four angular acceleration profiles was observed (Fig 3). Angular accelerations as large as ±1,500 rad/s² were measured during heel strike and toe off transients.

Root-mean-square (RMS) error values of all three gyro-based profiles with respect to the accelerometer-based profile resulted in approximately 50±3 rad/s². Maximum error ranged from 1,000 to 1,250 rad/s². Smoothing effects of averaging data from two gyros data were not apparent.

Noise amplification typically seen in numerical time derivatives of gyro signals was not observed due to accuracy of internal signal conditioning and analog-to-digital converters. The central difference formula provided higher-order truncation error, $O(\Delta t^2)$, without phase shift. However, error between gyro- and accelerometer-based profiles still existed during heel contact and toe off transients (Fig 3).

Gyro-based finite-difference angular acceleration measurements provide several advantages over dual accelerometer-based measurements: fewer parts, smaller IMU size and sensor-to-sensor misalignment. However, current data suggests accelerometer-based angular acceleration measurements may be desired to capture high transients, such as heel contact and toe off, or during more dynamic activity.

CONCLUSIONS
Digital MEMS inertial sensors were used to measure the angular acceleration of a foot during normal walking. Gyro-based angular accelerations resulted in reasonable agreements with superior accelerometer-based measurements, except for the heel contact and toe off transients.

REFERENCES
1. Sommer H.J., IMU Tutorial, GCMAS, 2010