Introduction
Disorders of the ankle and foot often result in pain and activity limitations, especially while ambulating on uneven terrain. Routine physical examination may reveal relatively normal walking patterns in these patients in the level exam room. Gait analysis provides more objective information regarding function, but these studies are conducted upon level walkways. Uneven surface conditions may provoke symptoms of these foot disorders, but very little has been published regarding ramp and side-slope walking. This study was conducted to quantify ankle and foot kinematics in normal subjects during side-slope and ramp walking.

Materials and Methods
Fifteen normal subjects were evaluated. Subjects were categorized into one of three arch types using bony arch index (BAI) using the navicular height to foot length ratio. Those with low arch and high arch were excluded. Hindfoot and forefoot motions were determined while the subjects walked on level ground, a side-slope, and a ramp. A six camera ExpertVision system was used with eleven reflective markers. The subjects walked at a self-selected velocity. Five trials were collected to determine the consistency of gait. Results were calculated as Eulerian angles using a custom-designed computer program. Kinematics of the stance phase of the gait were measured in 10 subjects in level walking and on the up and down sides of a 15° side-slope, focusing upon calcaneal-tibial (Cal-Tib) and metatarsal-calcaneal (Met-Cal) motions (degrees) in sagittal, coronal and transverse planes. Kinematics were determined in 4 additional subjects in level walking and on the up and down sides of a 15° ramp. A paired t-test was used to determine if there were any significant differences between level and side-slope walking, and between level and ramp walking (p<0.05).

Results
Cal-Tib and Met-Cal movement patterns were consistent between the 10 subjects in the side-slope walking and 4 subjects in ramp walking. Side-slope Walking (Fig. 1): Cal-tib motion in coronal plane was altered by side-slope up walking, which caused more eversion (7.0±2.8˚; p<0.0001), while side-slope down walking caused more inversion (6.7±2.8˚; p<0.0001) compared with level walking. Side-slope up walking caused more cal-tib dorsiflexion (7.1±2.1˚; p<0.0001) and side-slope down walking more plantarflexion (4.1±3.8˚; p<0.0001) compared with level walking. In the transverse plane, side-slope up walking caused more cal-tib external rotation (3.0±1.3˚; p=0.0011) and side-slope down walking more internal rotation (3.5±2.2˚; p<0.0001) compared with level walking. Met-cal motion was affected by walking surface, with side-slope up walking causing more inversion (7.1±1.9˚; p=0.0000) and side-slope down more inversion (4.9±2.4˚; p=0.0007) compared with level walking. In sagittal and transverse planes, the pattern of met-cal motion for the side-slope up and down resembled the level walking.

Ramp Walking (Fig. 2): In sagittal plane, ramp-up walking increased cal-tib dorsiflexion from 4.8±3.8˚ to 21.3±4.0˚ and ramp down to 14.9±5.3˚. Ramp-up walking changed mean cal-tib plantarflexion from -16.5±6.2˚ to -11.6±9.3˚ (p=0.0068), and ramp down -14.7±2.9˚ (p=0.0153). Total cal-tib sagittal plane motion in ramp-up walking increased from 21.3±5.7˚ to 32.9±7.0˚, and ramp down to 29.6±4.7˚. Coronal and transverse plane cal-tib motions were not appreciably changed in ramp-up or ramp-down walking. In sagittal plane, ramp-up walking increased met-cal dorsiflexion from 7.9±1.7˚ to 11.9±6.4˚, and ramp down to 11.7±3.4˚. Ramp-up walking increased met-cal plantarflexion from -3.4±0.8˚ to -2.2±5.1˚, and ramp down -0.4±7.4˚. Total sagittal plane met-cal motion in ramp-up walking increased from 11.3±1.7˚ to 14.1±2.0˚, and ramp down to 12.2±5.0˚. Coronal and transverse plane met-cal motions were not appreciably changed in ramp-up or ramp-down walking.

Discussion
These data provided valuable normative information regarding ankle and foot kinematics during walking in abnormal ground conditions. The largest changes in side-slope walking occurred in the coronal plane for both the hindfoot and forefoot. When the person walked on the side-slope with the foot on the upside at the slope, the foot shifted to eversion and with the foot on the downside, the foot shifted to inversion. The largest changes in ramp walking occurred in the sagittal plane for both the hindfoot and forefoot as the ramp-up walking increased dorsiflexion. Analysis of walking upon non-level surfaces will allow the assessment of efficiency of conventional and new treatment options for ankle and foot problems such as bracing and reconstruction operations.

Acknowledgements
This work was supported by a grant from the NIH AR44518.

References