INTRODUCTION:
Current designs of total ankle replacements (TARs) have still not yet fully reproduced the normal kinematics of human ankles, though they have demonstrated encouraging intermediate-term clinical results. Further development of a prosthetic design that restores normal ankle kinematics requires a better basic biomechanical understanding of the natural human ankle in the stance phase of gait.

Ankle motion is generally regarded as being controlled by the complementary roles of the peri-ankle ligaments and the articular surfaces. The present investigation was aimed to elucidate the role of the peri-ankle ligaments in controlling ankle motion in the stance phase of level gait. A ligament that contributes to controlling joint motion needs to be stably taut, because slack ligaments are not able to provide any force to stabilize attaching bones. We therefore hypothesized that the peri-ankle ligaments work synergistically in a specific combination of reproducible strain patterns, to control ankle motion during weight-bearing.

METHODS:
Eight fresh-frozen cadaver ankles were subjected to a cyclic loading sequence simulating the normal stance phase. Each specimen was mounted in an MTS based ankle applicator, and subjected to 600N of axial load. The ankle was flexed within the physiologic motion arc during gait, from 15 degrees plantarflexion to 10 degrees dorsiflexion, with 1 Hz loading rate, and the sequence was repeated for five cycles.

To monitor peri-ankle ligament strain, differential variable reluctance transducers (DVRTs) were sutured in the mid-substance of six ligaments: the anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), posterior talofibular ligament (PTFL), and the anterior, middle, and posterior bundles of the superficial deltoid ligament complex (ADL, MDL and PDL, respectively). The ADL and PDL were included only for the last six specimens, since we realized their possible involvement after two specimens were tested. The zero-strain state for each ligament was determined at incipient tautening, and ligament strain was defined as percent elongation of the DVRT relative to the zero-strain length (Figure 1). As a result, a positive strain value represents the ligament being strained.

Five specimens were also subjected to an extended range flexion test, to determine the ligament strain beyond the normal motion arc in stance phase. Quasi-static plantar- and dorsiflexion were applied under a reduced (300N) axial load, to avoid ligament rupture with excessive flexion. Strain values at 30° plantarflexion and 30° dorsiflexion were determined for each ligament, and the strain values at these positions were compared to the value at 0° flexion, to determine the effects of additional flexion on strain of the ligament. In these comparisons, the data were statistically analyzed with a paired t-test.

RESULTS:
In the dynamic strain behavior results (Table 1), the ATFL was continuously strained during the motion arc in only one specimen (#1), and was continuously or mostly slack in the remaining specimens. The CFL was not continuously strained in any specimen, but was often continuously or mostly slack. The PTFL was continuously strained in only one specimen (#2), but was often continuously or mostly slack. In the deltoid ligaments, the MDL was continuously strained in 3 specimens (#3, 4, 7), and was mostly strained in 1 specimen (#6). The ADL and PDL were mostly continuously or mostly strained in any specimen. Essentially, none of the six ligaments had a reproducible strain pattern suggestive of controlling ankle motion.

In the extended range tests, the MDL was slightly or nearly taut at all flexion positions (Table 2). At 0° flexion, the CFL was also slightly or nearly taut, while the other ligaments were slack. The ATFL and ADL were stretched with 30° plantarflexion, while the CFL, PTF and the PDL were stretched with 30° dorsiflexion (p < 0.05, all cases).

DISCUSSION:
In the dynamic strain behavior results, no reproducible strain pattern to stabilize joint motion was found in the peri-ankle ligaments. The peri-ankle ligaments, at least the six major anatomic structures here monitored, were not likely working as principal stabilizing structures to control ankle motion. On the other hand, the results of the extended range test suggest that the peri-ankle ligaments function when the ankle is out of the typical positions during stance phase. Stance phase ankle motion control therefore appears to be primarily from articular surface congruity, not from peri-ankle ligaments.

Figure 1: Typical transient ligament strain behavior in simulated stance phase, for 15° plantarflexion to 10° dorsiflexion, for lateral (A) and deltoid (B) ligaments. Positive values of ankle flexion represent plantarflexion, while negative values represent dorsiflexion.