Introduction: Hindfoot fusions are commonly indicated for patients with symptomatic hindfoot arthritis. However, the effect of hindfoot fusion on ankle loading is not well understood and this is of particular concern in patients with early osteoarthritic changes in the ankle. Cadaveric simulations of gait suggest that isolated subtalar fusion does not alter ankle loading mechanics; and altered ankle loading has only been described following additional fusions of the Choparts joints in Triple arthrodesis\(^1,2\). These findings were coincident with an increasing popularity of isolated subtalar fusion for symptomatic arthrosis of the subtalar joint and this operation is well tolerated by patients, despite a reported progression of ankle joint degeneration in up to 43% of patients within 5 years\(^3\). They may also contribute to clinical decision making in the setting of asymptomatic radiographic changes of the adjacent Choparts joints at the time of surgery in dictating the extent of the hindfoot fusion. While the effect of frontal plane plantar inclinations during simulated standing has demonstrated expected changes in ankle load distribution\(^4\), the effect of progressive hindfoot fusion on ankle loading under similar loading condition has not been reported. Therefore, the purpose of this study was to characterize the effects of commonly utilized hindfoot fusion techniques on the contact mechanics at the ankle joint during provocative (inverted/everted) loading. We tested the following hypotheses that i) provocative loading following isolated subtalar fusion would alter both the magnitude and distribution of ankle loading, ii) the alterations in contact mechanics would increase with incremental fusion of the other hindfoot joints.

Methods: Seven fresh-frozen cadaveric lower limbs were used in this study. Soft tissues around the middle third of the tibia were removed, and the tibia was potted in bonding cement (Bondo/3M, Atlanta Georgia, USA). Pressure sensitive film (5033, Tekscan, South Boston, MA, USA) was inserted in the ankle joint space (Fig. 1A) and secured to the posterior tibia. A small incision was cut on the posterior capsule to facilitate sliding the sensor into the joint and care was taken to not damage any ankle ligaments. Each specimen was tested in the intact and three fused conditions: subtalar, double (subtalar and talonavicular), and triple (subtalar, talonavicular, and calcaneocuboid) arthrodeses. For each fusion condition (including the intact condition), three foot positions were tested: the neutral position, a 10° inversion and a 10° eversion. The amount of inversion and eversion foot rotation was controlled by a 10° wedge placed below the foot. During the test, a 400N ground reaction force was applied to the plantar aspect of the foot while a 350N tensile load was simultaneously applied to the Achilles tendon (Fig. 1B). Contact stress in the ankle joint was exported to a custom Matlab program (MathWorks Inc., MA) for data analysis (Fig.2). Contact area, medial-lateral position of the center of stress (CoS), and the normalized peak stress (peak stress/total axial force) were calculated for each testing condition. A repeated measure analysis of variance (ANOVA) was performed to compare the contact stress parameters between the intact and three fusion conditions across the three foot positions.

Results: Contact Area: Following fusion, contact area decreased significantly (p<0.05) for neutral and eversion positions of the foot (Fig. 3A). Center of Stress: Each hindfoot fusion resulted in a medial shift of CoS in the neutral and eversion positions but did not vary significantly between fusion modalities (Fig. 3B). Normalized Peak Stress: Normalized peak stress was increased during inversion conditions for all fusion modalities compared to the intact state (Fig. 3C). Increases in normalized peak stress were observed with incremental fusion, but this was not significant.

Discussion: The results of this study support our first hypothesis that isolated fusion of the subtalar joint causes alterations in ankle joint contact mechanics. Our second hypothesis was not supported; sequential fusion of the other hindfoot joints did not cause any further significant changes in ankle loading. In the intact ankle there were small amounts of measured change in normalized peak stress during provocative loading and this coincided with significant changes in the location of loading. Following fusion of the subtalar joint, the location of contact stress shifted medially (significantly for eversion and neutral) and remained relatively fixed for all orientations of the foot. This suggests that subtalar joint motion plays an important role in normalizing the stress distribution at the ankle. Not surprisingly, then, provocative loading altered either contact area or normalized peak stress for all (subtalar, double and triple) fusion conditions. Although there was a significantly decreased contact area during eversion and neutral position, normalized peak stress only increased significantly during inversion. This is likely a result of the interplay of joint morphology and decreased talar motion as the result of the fusion; loading an inverted foot position with loss of frontal plane motion at the subtalar joint likely increases medial ankle joint loading. In addition to seeing more load medially, the ankle is more susceptible to transverse plane rotation in this position, as demonstrated by our
Significance: Ankle joint degeneration as a consequence of hindfoot fusion is of particular concern to orthopaedic surgeons. While isolated subtalar fusion may result in a clinically less stiff hindfoot, these results suggest that inferred altered loading at the ankle joint is similar to that of double and triple arthrodesis.

Acknowledgments:

Fig. 1 Experimental Setup. External loads were applied to the plantar aspect of the foot (400N) and Achilles tendon (350N). The pressure sensitive film was inserted in the joint space from a small opening in the anterior portion of the ankle capsule.
Figure 2. Colormetric Stress Map of the ankle. Example of ankle joint loading during simulated standing. The center of stress (CoS) is indicated by a small black and white diamond.
Figure 3. Ankle stress results. All data are reported as changes from the intact-neutral condition. (A) Contact area was reduced in all fusion conditions in the neutral and eversion states. (B) Center of stress (CoS) was medially shifted in all fusion conditions in the neutral and eversion states. (C) Normalized peak stress was greater in all fusion conditions in the inversion state. *, † indicates statistically different from intact condition, significance levels of $p < 0.05$ and 0.01, respectively.

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