Dynamic Simulation of the Crossover Toe Deformity

INTRODUCTION:

The “crossover toe deformity”, though incompletely defined, refers to an instable second metatarsophalangeal joint (MTPJ) that leads to a progressive migration of the second toe in a dorsal and medial direction [2,3]. The etiology is uncertain. One specific and controversial hypothesis states that a long second metatarsal causes abnormal loading beneath the second MTPJ during stance phase which over time causes the associated symptoms (i.e., increased plantar pressure) and observed toe migration [4].

A previous radiographic analysis study found no significant correlation between a long second metatarsal and the crossover toe deformity [4]. However, the inclusion of feet with a wide range of angular deformity may not be representative of subjects with severe changes. In the current study, we used a robotic gait simulator (RGS), cadaveric specimens and a surgical metatarsal lengthening process to further investigate this relationship. We hypothesize that increasing the length of the second metatarsal will increase plantar pressure beneath the second MTPJ, as well as cause the MTPJ angle to increase medially and dorsally in the frontal and sagittal plane respectively. Furthermore, the increased pressure on the second metatarsal head will subsequently unload the peak pressure underneath the first metatarsal.

METHODS:

Six cadaveric feet were used for this University of Washington Institutional Review Board approved study. Preparatory dissections included a mid-tibial transsection, exposure of the second metatarsal dorsally, and separation of nine extrinsic foot tendons. Elongation of the second metatarsal was achieved through a custom-made aluminum support bracket attached to the bone via two proximal bone screws and two distal hanger bolts. Once the bracket was installed, the metatarsal was transected and aluminum spacers of varying lengths (0.48mm, 2mm, 4mm, 6mm, 8mm) were inserted. The nuts on the distal hanger bolts were loose while the spacers were inserted and were subsequently retightened. The 0.48mm spacer was used as a control, having the same thickness as the bone saw blade used.

The in vitro dynamic gait trials were performed with the RGS, which simulated physiologic tibial motion, tendon loading, and ground reaction forces (GRF) on the cadaveric foot [1]. The RGS consists of the R2000, a 6-degree of freedom parallel robot and nine electromechanical force control tendon actuators with associated load cells. Stance phase was scaled to 10 seconds and the vertical GRF to half body weight.

A six-camera Vicon motion analysis system was used to register the pose of the tibia to the RGS and track the tibia kinematics with respect to the ground. Vertical GRF was measured with a force plate mounted to the RGS. The target tibia kinematics and vertical GRF were determined from in vivo data averaged from ten healthy subjects who performed four to five gait trials each. A pressure plate mounted on the force plate recorded the plantar pressure. Custom pressure masks were created from weight bearing radiographs of each foot and used to extract the peak pressure (PP) and pressure-time integral (PTI) under the bony landmarks of interest. Three trials were obtained at each second metatarsal length with: 1) the magnitude of the first peak and the entire second half of the vertical GRF within ±10% of its target in vivo force, 2) the extrinsic tendon force curves to within 10N root mean square error of their targets, and 3) a physiologic plantar pressure distribution.

The weight bearing anterior/posterior and medial/lateral radiographs were taken using a custom-loading frame at quarter body weight prior to surgical metatarsal elongation and after each spacer was inserted. Published techniques were used to measure the frontal MTPJ angle (Figure 1), sagittal MTPJ angle and functional second metatarsal length [4]. Statistical analysis was performed with a linear mixed effects model.

RESULTS:

An increase in second metatarsal PP (Figure 2) and PTI was significantly associated with an increase in second metatarsal length (PP slope = 56 kPa/mm, p = .0005; PTI slope = 229 kPa S/mm, p < .0001). A decrease in first metatarsal PP and PTI was borderline significantly associated with an increase in second metatarsal length (PP slope = -21, p = .029 kPa/mm; PTI slope = -112 kPa S/mm, p = .024). An increase in MTPJ frontal angle was significantly associated with an increase in second metatarsal length (slope = 0.6 °/mm, p = .0003) but sagittal angle was not (slope= -0.4 °/mm, p = .3).

DISCUSSION:

This study explored the relationship between second metatarsal length and the crossover second toe deformity. A better understanding of this association is crucial to understanding the etiology of the deformity as well as to further develop prevention and treatment strategies. Similar to a previous study investigating Morton’s foot structure and plantar pressure [5], our results support a positive correlation between second metatarsal length and peak pressure underneath the second MTPJ. Differing from the first MTPJ, the second MTPJ capsule and soft tissue structures are not designed to support the large stance phase loads. It is thought that prolonged exposure to the plantar pressures seen in our study would lead to the observed subluxation and dislocation seen in this joint of crossover toe patients.

The consistent medial deviation seen with elongation of the second metatarsal also relates directly to symptoms observed in patients afflicted with the deformity. While a definite mechanism to explain these results is not attainable from this study, we speculate that the peak pressure beneath the MTPJ may be orientated such that a consistent deviation is seen over time.

Although significant correlations were not found with the sagittal plane angle, this is due to limitations within our study, more specifically, our inability to reproduce the prolonged deterioration of the MTPJ capsule. Further research into the long-term effects of an elongated second metatarsal would supplement these results and possibly unveil a more detailed picture of the deterioration occurring at the joint.

REFERENCES:


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