Arthrodesis of the First Metatarsophalangeal Joint: A Robotic Cadaveric Study of the Effect of Dorsiflexion Angle on Plantar Pressure

INTRODUCTION:
Arthrodesis of the first metatarsophalangeal joint (MTPJ) is indicated for arthropathy of the joint, particularly osteoarthritis, or for patients requiring revisions of failed surgeries [1]. In this study we simulated fusion of the first metatarsal with the proximal phalanx in cadaveric specimens and subjected the specimens to dynamic gait simulation. The literature suggests an optimum fused dorsiflexion angle in the range of 20° to 25° [2]. Clinical studies have reported hallux plantar pressure following arthrodesis, both qualitatively [3] and quantitatively [4][5], but no correlation has been proposed between the fused dorsiflexion angle and the plantar pressures recorded during postoperative gait. A finite element model demonstrated a dependency of hallux pressure on the fused dorsiflexion and valgus angles [6]. We hypothesize that there exists an optimal first MTPJ fused dorsiflexion angle at which plantar pressures are minimized.

METHODS:
Six cadaveric trans-tibial foot specimens with no evidence of surgery or preexisting deformity were approved for use by the institutional review board. The nine extrinsic foot tendons of the foot were exposed mid-tibia, and the dorsal surfaces of the head of the 1st metatarsal (MTH) and the base of the proximal phalanx were reduced. Steel bolts (Hanger Bolt & Stud; Greenfield, IN) were embedded into the bones and mated with custom, interchangeable aluminum plates that achieved incremental changes in dorsiflexion angle and accommodated translation of the joint’s center of rotation. Load-bearing radiographs were obtained to associate each plate with a true mid-diaphyseal dorsiflexion angle. Finite element analysis validated the rigidity of the plates, and the repeatability of the plate fixation process was confirmed through pilot studies of the dorsiflexion angle (± 0.7° across plate changes; ± 0.6° across user measurements). For each foot, plates were selected to span a mid-diaphyseal range of approximately 10° to 30° of dorsiflexion.

Simulated gait was achieved via the robotic gait simulator (RGS) [7] consisting of the R-2000 Rotopod™ (Parallel Robotics Systems; Hampton, NH) and linear electromechanical actuators (Exlar; Chanhassen, MN). A six-camera motion analysis system (Vicon; Lake Forest, CA) registered the position of the foot relative to the R-2000. A force plate mounted perpendicular to the R-2000 platform moved along the inverse trajectory of theibia based on kinematic and kinetic data from in vivo studies [7]. The actuators applied variable dynamic tension to the tendons based on trajectories derived from EMG data of muscle activity. Load cells placed in series with the actuators recorded tendon forces, and plantar pressure was recorded using a PEDAR insole mounted parallel to the R

RESULTS:
Data from six feet demonstrate that PP (Figure 1) and PTI under the hallux were negatively correlated with dorsiflexion angle (p<0.005). PP and PTI under the MTH were positively correlated with dorsiflexion angle (p<0.005). The angle at which the regression lines intersected was 24.0° for PP (Figure 1) and 20.8° for PTI. All tendon force trajectories satisfied the fidelity criterion of ± 10N RMS error. A qualitative assessment showed that Achilles tendon performed with the greatest fidelity. Averaged across all trials, the peak vertical GRF at heel-strike had an error of 5.9%, and the peak vertical GRF at push-off had an error of 3.3%.

DISCUSSION:
An understanding of the optimum fused dorsiflexion angle is key to preventing abnormal plantar pressures following arthrodesis. While the intersections of the regression lines reduce cumulative pressures, the selection of an optimum is more nuanced. Our results of 24.0° for PP and 20.8° for PTI support the suggested range of 20° to 25° [2].

We are unaware of previous studies that have examined the angle-pressure relationship in postoperative gait. Discrete values have been reported, however, for static stance. Gibson and Thomson [4] reported a dorsiflexion angle of 26°± 7° and a valgus angle of 9°± 6° at one year following arthrodesis. Pressure was reported at two years following surgery, averaging 23 ± 10.6 N/cm² under the MTH. DeFrino et al. [5] reported a dorsiflexion angle of 15.7°± 6.9° and normalized pressures of 0.51 N/cm² kg and 1.13 N/cm² kg under the MTH and the hallux, respectively.

One limitation of our study was the lack of valgus angle control between feet. An investigation into the impact of valgus variation is in progress. Analysis of pressure data for the head of the second metatarsal has also been initiated. It should be noted that the resolution of pressure measurement (99 sensors across insole) was relatively coarse.

Future studies should increase gait from 1/15th physiologic velocity and 50% simulated body weight to better approximate physiological conditions. Similarly, the RGS may be driven by kinematics and kinetics from postoperative gait in arthrodesis patients [8]. An examination of the effects of fused coronal rotation would supplement the current findings.

REFERENCES:

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