First Metatarsal Osteotomies for Correction of Hallux Valgus: A Finite Element Model

Philippe Favre, Samy Bouaicha, Jess G. Snedeker, Norman Espinosa
Department of Orthopaedics, Balgrist, University of Zurich, Zurich, Switzerland
pfavre@research.balgrist.ch

Introduction: Hallux valgus affects 2-4% of adults and is one of the most common orthopaedic deformities. In order to treat this condition, several types of first metatarsal head (MTH1) osteotomies have been developed. Because the MTH1 bears up to 30% of the ground reaction force during the stance phase [1], many experimental studies have considered the mechanical resistance and load to failure of these different procedures on cadaver or synthetic bone [2]. The stress distribution in the whole foot [3] or the intact MTH1 alone [4] have been modelled using the finite element method. Although the experimental investigations delivered valuable information on primary stability of the fixation, and the finite element studies brought new insights in the mechanics of the normal foot, the stress pattern in the osteotomized MTH1 for the correction of the hallux valgus remains yet unknown. The present finite element study investigates the deformations in the intact MTH1, as well as in the scarf, chevron and reversed-L osteotomies when the forefoot loading is highest. This is of prime importance to optimize the mechanical resistance, stability and healing of these procedures.

Materials and Methods: A 3D finite element model of the MTH1 was constructed, based upon the anatomy of a healthy foot made available online [5]. The intact MTH1 was first tested alone and served as a reference for comparison with the osteotomy models. The scarf, the modified chevron and the reversed-L osteotomies were successively performed in Abaqus/CAE (Simulia, Providence, RI). For the scarf osteotomy, a Z-cut was defined at the diaphyseal level, the distal and proximal fragments being cut at 45° angles. The distal apex was positioned 10mm from the metatarsophalangeal joint. The apex of the chevron cut was centered in the midline of the MTH1 and positioned 5mm proximally from the metatarsophalangeal joint, with a 60° angle between both arms of the cut. For the reversed-L osteotomy, the apex of the cut was localized midways between the dorsal and plantar cortices, 10mm proximal to the metatarsophalangeal joint. The plantar arm was parallel to the plantar plane and the dorsal arm was cut perpendicularly. In all tested osteotomies, the distal fragment was shifted 5mm laterally without angular correction. The geometries were then imported in MSC.MARC/Mentat (MSC Software Corporation, Los Angeles, CA) for finite element meshing and analysis. The geometries were used to generate a volumetric mesh of 8-node linear hexahedral elements to model the trabecular bone, on which a surface mesh of 4-node quadratic shell elements was superimposed to model the cortical bone. Based on observations of CT scans of the MTH1, an average thickness of 2mm was attributed to all cortical elements, and trabecular elements were left only in the proximal and distal thirds. This yielded an average of 45000 elements per model. Linear elastic material properties (Elastic modulus of 17 GPa for cortical, 5.5 MPa for trabecular bone and Poisson’s ratio of 0.3 for both) were applied. The nodes of the distal and proximal fragments situated at the interface of the cut where glued together to model a perfectly bonded cut, as in a healed osteotomy. The boundary conditions were chosen to reflect the situation where the foot is most heavily loaded, to simulate the worst case scenario. A bodyweight of 70kg was assumed. Jacob estimated the sum of all muscle and external forces exerted on the MTH1 at push off [6]. This resultant force reaches 119% bodyweight and is oriented dorsally with a 13° angle to the longitudinal axis of the MTH1. Finally, the proximal end of the MTH1 was fixed in space [4].

Results: In the intact MTH1, the maximal von Misses stresses were located on the dorsal side of the bone. In all osteotomized MTH1, the lateral side of the proximal fragment was most heavily loaded, with values 3.6 times higher in the scarf, 2.2-fold in the chevron and 1.7-fold in the reversed-L than in the intact MTH1. Equivalent von Misses stress distribution in the intact (a), scarf (b), chevron (c) and reversed-L (d) MTH1. On the right, view from lateral; on the left, view from dorsal. The red arrow on the intact MTH1 shows the applied force vector, similar in all models.

Discussion: This is the first study that investigates the stresses induced by osteotomies of the MTH1. It indicates that the loading of the MTH1 is greatly influenced by the osteotomy technique. The intact MTH1 is mainly loaded in compression and dorsal bending, inducing the observed higher stresses at the dorsal aspect of the bone. With the osteotomy, the distal fragment is shifted laterally and the force is further transmitted largely through compression of the lateral side of the proximal fragment. Moreover, this throws the axial component of the external force off-center from the axial axis of the bone, inducing a bending moment in the lateral direction that additionally loads the lateral side. The cut in the chevron and reversed-L is located distally, leaving the lateral cross-section of the proximal fragment intact for load bearing. In the chevron, close to the apex of the cut, the presence of the two arms on a same cross-section of the proximal fragment lead to slightly higher stresses than in the reversed-L cut. On the other hand, the scarf removes the inferior half from the proximal fragment, leaving less bone bear force, and leading to the comparatively higher stresses. For optimal load transfer, the scarf cut should therefore be made close to the plantar aspect as possible in order to increase the amount of bone available on the lateral side of the proximal fragment. A sensitivity analysis revealed that the material properties of the trabecular bone do not influence the results, but its spatial distribution does. Further developments will include a more accurate representation of the trabecular bone distribution, modelling of the screw fixation and assessment of primary stability.