Medical Engineering and Physics 42 (2017) 80–90

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Total ankle replacement design and positioning affect implant-bone micromotion and bone strains

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ARTICLE INFO

Article history:
Received 14 June 2016
Revised 12 January 2017
Accepted 31 January 2017

Keywords:
Total ankle replacement
Fixation
Micromotion
Malpositioning
Finite element modelling

ABSTRACT

Implant loosening – commonly linked with elevated initial micromotion – is the primary indication for total ankle replacement (TAR) revision. Finite element modelling has not been used to assess micromotion of TAR implants; additionally, the biomechanical consequences of TAR malpositioning – previously linked with higher failure rates – remain unexplored. The aim of this study was to estimate implant-bone micromotion and peri-implant bone strains for optimally positioned and malpositioned TAR prostheses, and thereby identify fixation features and malpositioning scenarios increasing the risk of loosening. Finite element models simulating three of the most commonly used TAR devices (BOX®, Mobility® and Salto®) implanted into the tibia/talus and subjected to physiological loads were developed. Mobility and Salto demonstrated the largest micromotion of all tibial and talar components, respectively. Any malpositioning of the implant creating a gap between it and the bone resulted in a considerable increase in micromotion and bone strains. It was concluded that better primary stability can be achieved through fixation nearer to the joint line and/or while relying on more than a single peg. Incomplete seating on the bone may result in considerably elevated implant-bone micromotion and bone strains, thereby increasing the risk for TAR failure.

1. Introduction

Total ankle replacement (TAR) can provide arthritis patients with pain relief and improved ankle range of motion, and is therefore gaining popularity as an alternative to arthrodesis [1,2]. The currently used semi-constrained cementless designs with mobile-bearing polyethylene (PE) insert have shown promising results [2].

Loosening of the tibial or talar component is the primary indication for TAR revision (19–47%, [3–7]). High levels of micromotion of cementless orthopaedic prostheses (>50–150 µm; [8–10]) are thought to impede osseointegration at the bone-implant interface, thereby hampering fixation [11] and potentially leading to clinical loosening [8,9,12]. Accordingly, micromotion of two TAR prosthesis designs has been assessed experimentally to evaluate the implant primary stability using optical tracking [13].

A useful tool to assess initial micromotion of joint replacement implants and peri-implant bone strains is finite element modelling (FEM) (e.g. hip, [14,15]; shoulder, [16–18]). Several studies have employed FEM to explore the performance of current TAR devices: Terrier et al. [19–21] modelled the Salto® implanted in the tibia to explore bone strains and stresses occurring at the implant vicinity. Espinosa et al. [22] developed a model to study contact pressures occurring in the PE component of the Agility® and Mobility®. Reggiani et al. [23] included ligaments in a FE model to investigate the kinematics and contact pressures of the BOX®. However, to our knowledge, no FE study has investigated TAR implant-bone micromotion.

Manufacturers of TAR prostheses provide detailed guidelines for their positioning during arthroplasty surgery. Proper implant positioning is necessary for achieving good clinical results [24,25], and even a slight degree of malpositioning has been claimed to result in higher failure rates [26]. Malpositioning of TAR has also been investigated in biomechanical settings. Saltzman et al. [24] found that elongation of the tibiocalcaneal ligament was considerably increased by varus/valgus malpositioning, and Espinosa et al. [22] found that such malpositioning increased pressures acting on the mobile component, which could lead to premature PE wear. Varus/valgus and dorsi-/plantar-flexed malpositioning of TAR components reported in the literature [27] may lead to a gap between the implant and the bone (often seen clinically

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http://dx.doi.org/10.1016/j.medengphy.2017.01.022

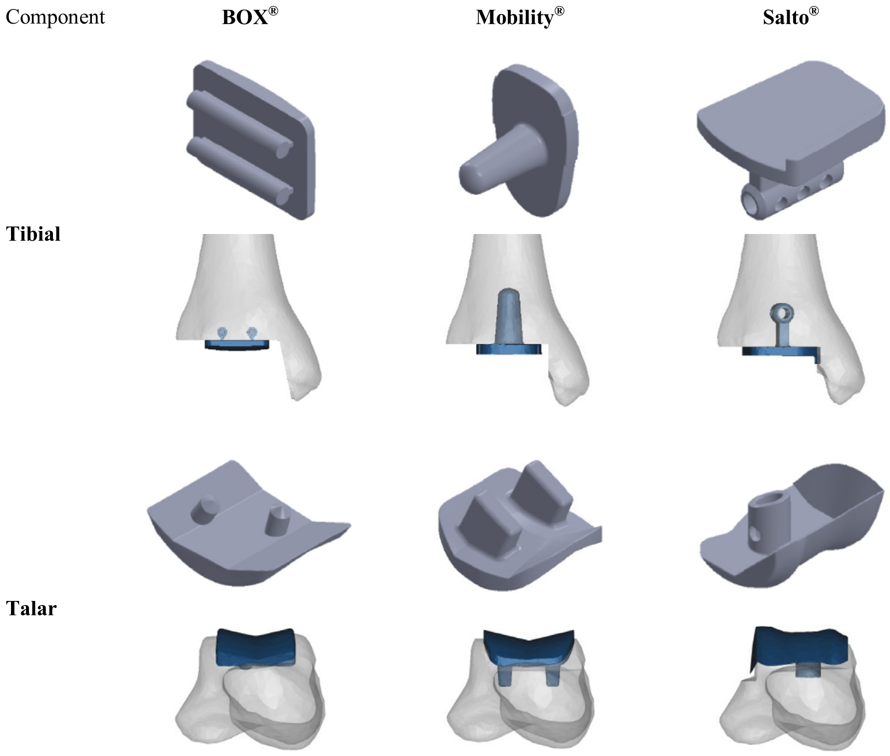

Fig. 1. Geometrical computer-aided-design models of the tibial and talar components of the three total-ankle-replacement (TAR) prostheses explored in the study; the positioning of each design with respect to the bone is also shown from a frontal view. Both BOX® components achieve fixation to the bone closest to the joint line (fixation features anchored to the dense distal tibial or proximal talar bone) and via two fixation pegs. The tibial Mobility® and talar Salto® components achieve fixation to the bone furthest from the joint line (fixation features extended deeper into the less dense trabecular bone) and via a single peg each. The Salto® talar component has a flange that covers the lateral facet of the talus (after bone resection).

on post-operative x-rays), which is likely to result in increased micromotion (as identified in a study assessing micromotion of a prosthetic glenoid, [16]). However, despite these clinical observations, the impact of TAR malpositioning on implant primary stability remains unexplored.

The aim of this study is to use *in silico* modelling to calculate implant-bone micromotion and peri-implant bone strains of the tibial and talar components of current TAR designs when optimally positioned and malpositioned. These data will identify fixation features and positioning scenarios that place the ankle prosthesis at higher risk of early loosening. The findings can be useful for surgeons and implant designers when planning the arthroplasty procedure.

2. Methods

2.1. Geometrical modelling

The geometries of the BOX® (MatOrtho, Leatherhead, UK), Mobility® (DePuy, Warsaw, IN, USA) and Salto® (Tornier, Amsterdam, The Netherlands) TAR designs – which have been three of the most commonly implanted TAR devices in the 2010s according to national joint replacement registries [3–7] – were reverse-engineered from production specimens using a digital Vernier Calliper, micrometer and digital photography by means of computer-aided-design software (SolidWorks®, Education Edition, 2011–12; Dassault Systèmes, France) (Fig. 1).

A cadaveric leg cut below the knee joint (female, age 79 years, height 170 cm, body mass 59 kg, no known bone or leg anatomical abnormalities) was CT-scanned in a 'neutral' position (approximately 90° between the posterior calf and the sole of the foot) using a Definition AS® Computed Tomography (CT) scanner (Siemens Healthcare, Erlangen, Germany); axial voxel sizes were set to approximately 0.56 mm and slice thicknesses were 0.6 mm. Geometrical models of the tibia and talus were then generated using MIMICS® (version 16.0; Materialise NV, Leuven, Belgium).

Implant sizes were rescaled according to the subject's anatomy. Virtual implantations were performed in Rhinoceros® (version 4.0; Robert McNeel & Associates, Seattle, WA, USA) according to the surgical guidelines provided by the prosthesis manufacturers [28–31]. Briefly, the surgical technique requires the distal tibia to be cut in the anteroposterior direction with a drill and/or sagittal saw, using a designated instrument to align the cuts appropriately. The talar surface is then exposed by plantarflexing the foot, and holes for pegs are drilled in the superoinferior direction. In addition to the 'optimal' position, several types of malpositioning were simulated, including varus/valgus and dorsiflexed positioning of the tibial component, as well as implant positioning with and without a 1–2 mm gap between the tibia/talus and implant component (Fig. 2). These represent the most common and worrying types of TAR malpositioning, as determined from the literature [22,24,26,27,32,33] and through consultation with an orthopaedic surgeon specialised in foot and ankle surgery (JC), who supervised the 'virtual implantation' process.

2.2. Material properties

Implants were assigned a Young's modulus of 210 GPa and Poisson's ratio of 0.3 to represent CoCr alloy. Bone was assigned a Poisson's ratio of 0.3, and each element of the FE model was assigned an individual elastic modulus that depended on the average CT greyscale value (in Hounsfield Units, HU) of all voxels contained within the element volume according to equations derived in previous studies [34–37], as described in the following empirical