Journal of Orthopaedic Translation (2017) xx, 1—11

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: http://ees.elsevier.com/jot

JOURNAL OF ORTHOPAEDIC TRANSLATION

ORIGINAL ARTICLE

Finite element analysis of biomechanical effects of total ankle arthroplasty on the foot

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Received 25 August 2017; received in revised form 8 December 2017; accepted 11 December 2017

KEYWORDS
Ankle prosthesis;
Bone stress;
Finite element analysis;
Joint contact pressure;
Plantar pressure;
Total ankle arthroplasty

Abstract *Background:* Total ankle arthroplasty is gaining popularity as an alternation to ankle arthrodesis for end-stage ankle arthritis. Owing to the complex anatomical characteristics of the ankle joint, total ankle arthroplasty has higher failure rates. Biomechanical exploration of the effects of total ankle arthroplasty on the foot and ankle is imperative for the precaution of postoperative complications. The objectives of this study are (1) to investigate the biomechanical differences of the foot and ankle between the foot with total ankle arthroplasty and the intact foot and (2) to investigate the performance of the three-component ankle prosthesis.

Methods: To understand the loading environment of the inner foot, comprehensive finite element models of an intact foot and a foot with total ankle arthroplasty were developed to simulate the stance phase of gait. Motion analysis on the model subject was conducted to obtain the boundary and loading conditions. The model was validated through comparison of plantar pressure and joint contact pressure between computational prediction and experimental measurement. A pressure mapping system was used to measure the plantar pressure during balanced standing and walking in the motion analysis experiment, and joint contact pressure at the talonavicular joint was measured in a cadaver foot.

Results: Plantar pressure, stress distribution in bones and implants and joint contact loading in the two models were compared, and motion of the prosthesis was analysed. Compared with

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https://doi.org/10.1016/j.jot.2017.12.003

the intact foot model, averaged contact pressure at the medial cuneonavicular joint increased by 67.4% at the second-peak instant. The maximum stress in the metatarsal bones increased by 19.8% and 31.3% at the mid-stance and second-peak instants, respectively. Force that was transmitted in three medial columns was 0.33, 0.53 and 1.15 times of body weight, respectively, at the first-peak, mid-stance and second-peak instants. The range of motion of the prosthetic ankle was constrained in the frontal plane. The lateral side of the prosthesis sustained higher loading than the medial side.

Conclusion: Total ankle arthroplasty resulted in great increase of contact pressure at the medial cuneonavicular joint, making it sustain the highest contact pressure among all joints in the foot. The motion of the prosthesis was constrained in the frontal plane, and asymmetric loading was distributed in the bearing component of the ankle prosthesis in the mediolateral direction.

The translational potential of this article: Biomechanical variations resulted from total ankle arthroplasty may contribute to negative postoperative outcomes. The exploration of the biomechanical performance in this study might benefit the surgeons in the determination of surgical protocols to avoid complications. The analysis of the performance of the ankle prosthesis could enhance the knowledge of prosthetic design.

Introduction

Total ankle arthroplasty (TAA) is gaining popularity due to the concept that it can provide more functional movements than ankle arthrodesis for reconstruction of degenerative ankles with end-stage arthritis. However, clinical reports have indicated a wide range of iatrogenic complications and a low success rate [1,2] in TAA surgeries. Failure rates were reported to range from 10% to 20% within 10 years after surgery [3–10]. Some failures required conversion to ankle arthrodesis [11], and in extreme cases, led to amputation [4].

Surgical failures may be a result of the fact that prostheses cannot totally resemble natural human ankles, which have complex anatomical structures, sophisticated kinematics and intimate interactions and stabilization mechanisms. Sufficient understanding of the biomechanics of TAA is imperative. Previous biomechanical investigations, including gait analyses [12–19], cadaveric experiments [17,20,21] and radiographic observations, provided useful, but insufficient, exploration of the inner foot. Computational methods are featured to provide insight into human bodies and have been widely used in biomechanical observations.

Finite element (FE) models of TAA have been developed and used to investigate the contact pressure and kinematics of the implants during gait [22]; to evaluate the effects of alignment of prosthesis components [23]; to postulate the bone-remodeling process after TAA [24]; to identify the failure mechanism of the polyethylene component [25] and to further investigate other clinical issues under physiological loading conditions [26]. Precisely, an FE model of TAA with the foot–ankle complex was used to investigate plantar pressure and stress distribution in bones in balanced standing [27]. Models constructed in these studies were based on partial foot segments, which were insufficient for observing the biomechanics of the entire foot and ankle. In this study, FE models of an intact foot and a foot with TAA were developed to (1) evaluate the influence of TAA on the foot biomechanics in terms of plantar pressure, joint contact pressure, bone stress distribution and force transmission and (2) investigate the motion and loading distribution of the ankle prosthesis.

Materials and methods

Ethical approval for this project was granted by The Hong Kong Polytechnic University Human Subject Ethics Subcommittee (reference number HSEARS20070115001). The participant who participated in the gait experiment was informed of the experimental procedures and gave written informed consent for the participation in the magnetic resonance image (MRI) scanning, gait experiment and for publishing the case details without disclosing the participant's identity.

Development of finite element models

An FE model of the intact foot [28,29] involving 28 bones, 103 ligaments, plantar fascia, nine groups of extrinsic muscles and a bulk of encapsulated soft tissue was developed (Fig. 1). A female participant, aged 29 years with a body mass of 54 kg and a height of 165 cm, was recruited to acquire the MRI (2 mm slice interval, 3.0T, Siemens, Erlangen, Germany) of the right foot. She claimed to have no history of lower limb injuries or pathologies. Geometries of 28 bones and foot surface were reconstructed from the MRI using Mimics software (Materialise, Leuven, Belgium) and further edited into an FE model using Abaqus software (Dassault Systèmes Simulia Corp., Providence, RI, USA). The interphalangeal joints of the four lesser toes were simplified as a connection using a 2-mm thick soft layer, while other articulations were defined as frictionless surface-to-