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Finite element analysis of the amputated lower limb: A systematic review and recommendations

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ABSTRACT

The care and rehabilitation of individuals after lower limb amputation presents a substantial and growing socioeconomic challenge. Clinical outcome is closely linked to successful functional rehabilitation with a prosthetic limb, which depends upon comfortable prosthetic limb – residual limb load transfer. Despite early interest in the 1980s, the amputated limb has received considerably less attention in computational biomechanical analysis than other subjects, such as arthroplasty. This systematic literature review investigates the state of the art in residual limb finite element analysis published since 2000. The identified studies were grouped into the following categories: (1) residuum-prosthesis interface mechanics; (2) residuum soft tissue internal mechanics; (3) identification of residuum tissue characteristics; (4) proposals for incorporating FEA into the prosthesis fitting process; (5) analysis of the influence of prosthetic componentry concepts to improve load transfer to the residuum, such as the monolimb and structural socket compliance; and (6) analysis of osseointegrated (OI) prostheses. The state of the art is critically appraised in order to form recommendations for future modeling studies in terms of geometry, material properties, boundary conditions, interface models, and relevant but un-investigated issues. Finally, the practical implementation of these approaches is discussed.

1. Introduction

The care and rehabilitation of individuals after lower limb amputation presents a substantial and growing socioeconomic challenge. The International Society for Prosthetics and Orthotics reports that there is a recognized need for advanced technology in prosthetic limb componentry and its provision, and there is a desire in the clinical community to enhance evidence-based practice [1].

Rehabilitation after amputation commonly aims to restore functional independence through promotion of ambulation using a prosthetic limb. Fitting a conventional prosthetic limb employing a socket for suspension commonly requires an iterative and labor-intensive process [2,3]. This is partially a consequence of changes in the residual limb soft tissues, including their volume, shape, tissue composition, sensitivity, and scarring from surgical wounds. These factors may vary during the course of a day due to temperature, activity and hydration, or over several months, as postoperative oedema subsides, muscles atrophy and soft tissues remodel to enable socket-skeleton load transfer [4–6].

The extent and duration of comfortable load transfer to the residual limb changes during rehabilitation, and there are considerable challenges in identifying physiologically-informed biomechanical targets for the socket's design. Instead, prosthetists aim to produce an acceptable definitive socket by using their experience and patient feedback with iteratively adjusted trial sockets. Short term changes in the residuum are typically managed using socks and soft 'Pelite' polymer foam or silicone gel liners. However, ill-fitting sockets are still common for this population, affecting an individual's quality of life through discomfort and functional limitations, causing secondary musculoskeletal conditions such as osteoarthritis, osteoporosis, and lower back pain [7].

In below knee amputation (BKA) surgery, a soft tissue pad is created over the resected tibia and fibula comprising the gastrocnemius and soleus muscles. The pad is sutured to the anterior tibial periosteum or the bone, and a posterior or skewed flap of skin seals the site. When a conventional, socket-suspended prosthesis is used, the muscles, predominantly subject to tensile loading along the fiber direction, are therefore subject to shear and transverse compression. Strain concentrations are also experienced

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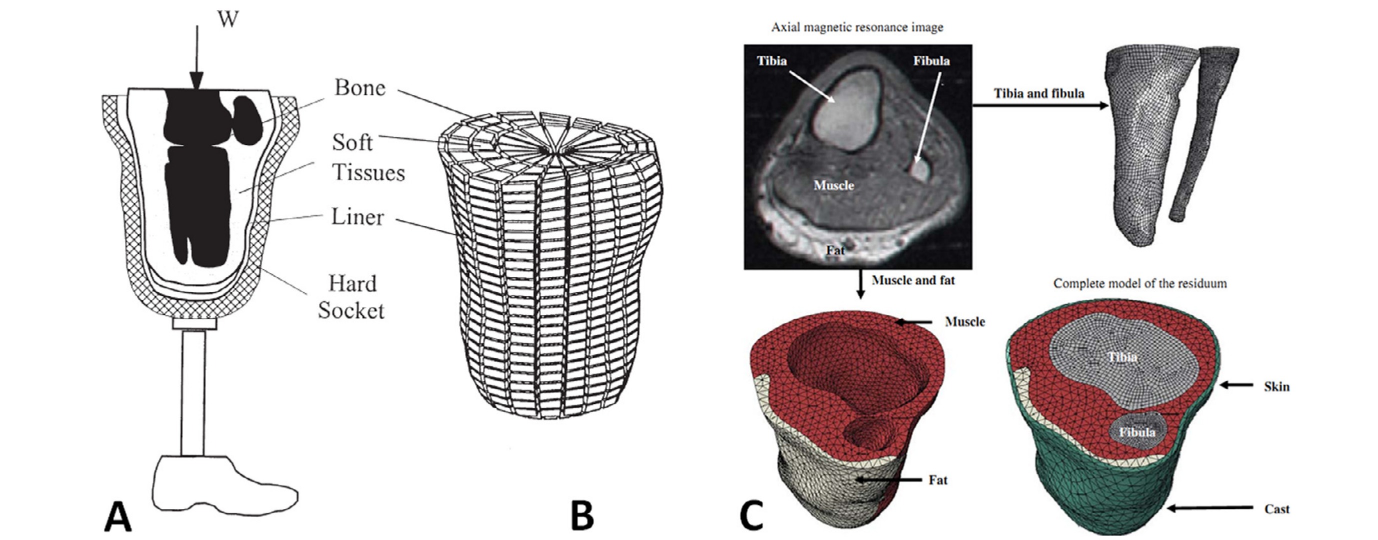

Fig. 1. Examples of published residual limb FE models, intended to represent loading through a prosthetic socket and liner with multiple bone models (A,B), and to represent an upright-MRI scan scenario loading through a plaster cast (C). Reproduced from: A,B) Reprinted from [26] with permission from Elsevier (license 3,973,140,409,695), and C) Reprinted from [46] with permission from Elsevier (license 3,973,140,811,893).

around bony prominences, such as the anterior edge of the tibia. Furthermore, the soft, relatively non-load bearing skin covering the calf, patella tendon, tibial plateau and anterior tibial surface becomes the primary load transmitting interface, and experiences substantial cyclic pressure and shear. In above knee amputation (AKA), similar changes in loading may be experienced by the skin and adductor muscles at the distal femur, and by the proximal soft tissues around the ischiopubic ramus and greater trochanter bony prominences. Alternatively, a prosthetic limb may be suspended by an implant, fixed directly to the residual bone by osseointegration (OI).

The residuum–prosthesis interface is the site at which the majority of early complications are observed during rehabilitation, and is directly influenced by the custom-designed prosthetic socket, liners and socks, and how they are used. The incidence of skin disorders is substantial [8], resulting from the requirement to transmit elevated compressive and shear forces between the prosthesis and residual limb. The residuum tissues are not used to bearing normal compressive and shear load, as the plantar tissues in the foot are [9,10]. Incorrect socket fit can potentially lead to dermatologic problems such as contact dermatitis [8] and keratosis [11], and in serious cases, internal tissue strain and ischemia can lead to deep tissue injury [12]. Discomfort and the risk of skin breakdown are elevated with a moist climate due to perspiration, and prolonged exposure to the chemical compounds of the prosthesis [13]. These problems can arise in established residual limbs with no history of skin problems as a result of changes in liner and socket prescription, as well as the environment at the interface. For example, the process by which patients apply a liner to their residual limbs prior to donning a socket may introduce trapped air, which can influence skin friction, temperature and potentially lead to blistering [14].

The residuum tissues must adapt to their changed mechanobiological duties, which is a lengthy and uncomfortable process. Important progress has been made towards understanding the tissues' sustainable threshold levels of strain magnitude and duration [15] the adaptive processes are highly variable, and not fully understood. Finite element analysis (FEA) is a type of numerical modeling which, when applied to the residual limb (Fig. 1) has potential to offer insights into soft tissue load distributions and magnitudes, which may provide an evidence base to assist prosthetists with socket design, allowing rehabilitation to be expedited with reduced discomfort and treatment expense [16]. It also enables pre-clinical analysis of novel prosthetic componentry, such as OI implant-suspended concepts.

This paper reports a systematic review of the literature, up to January 2017, considering the application of FEA methods to analyze the residual tissues in the amputated lower limb, and their interface with prosthetic componentry, nominally sockets, liners and osseointegrated implants. The review's objective was to identify the state of the art in numerical analysis considering recent trends in modeling approaches and objectives, experimental validation, interface models, tissue material models, derivation of anatomic geometry, and applied loading and boundary conditions. Furthermore, the range of study questions and model output measures was evaluated, and a discussion of future research possibilities is proposed. In order to facilitate this work, reference is made to a range of clinical reports which may provide appropriate model input data or be employed for modeling corroboration, and measurement techniques for validation. Finally, comments are made regarding the potential for practical implementation of these techniques to answer the prosthetic and orthotic community's needs.

2. Methodology

2.1. Search strategy

This systematic literature review employed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach [17]. Two databases (Web of Science and PubMed) were searched for relevant articles using the following keywords:

(finite element) AND ((transtibial OR trans-tibial OR below knee) OR (transfemoral OR trans-femoral OR above knee) OR disarticulation) AND (amput*)

For each article, the reference lists and forward-citation reports from each database were consulted in order to identify additional relevant articles that were not found in the automatic search.

2.2. Study selection

Primary eligible articles were selected from the full list of automatically retrieved articles. This review aimed to capture original research involving finite element analysis of the residual lower limb following amputation. Therefore, review articles, and