Internal Mechanical Conditions in the Soft Tissues of the Residual Limb in Trans-Tibial Amputees

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INTRODUCTION

During a trans-tibial amputation (TTA), the posterior muscles are folded over the distal end of the truncated tibia and fibula. This creates a muscular flap that is pressed transversely by the truncated bones during load-bearing. Patients recovering from TTA who wish to remain active in daily routines, use prostheses. Unfortunately, TTA patients often suffer from pain, blisters, edema, pressure ulcers and flap necrosis caused by prosthetic misfit. These complications often lead to further amputation and even death. Recently, a perilous injury condition was identified, and termed as "deep tissue injury" (DTI).[1] Deep tissue injury is a muscle lesion under intact skin that results from compression of the muscle flap by the truncated bones against the socket. Knowledge of DTI aetiology is yet to be established and is mostly hindered by the inability to measure deep tissue stresses and strains directly and un-intrusively. We therefore use patient-specific finite element (FE) analyses to calculate *in-vivo* muscle flap stresses and strains.[2]

AIMS AND OBJECTIVES

The first objective of this study is to characterize the mechanical conditions that evolve in the muscle flap of the residual limb of TTA patients after donning the prosthetic socket and during load-bearing. The second objective of this study is to develop a method that will ultimately be able to identify the risk for DTI in prosthesis-users and improve the fitting of the prosthesis, based on integration of data from pressure measurements between the residual limb and the socket of the prosthesis and patient-specific FE modelling.

METHODS

Two thin and flexible pressure-sensing mats were designed specifically for this project jointly by our laboratory and Sensor Products Co. (NJ, USA). The dimensions of the mats were selected according to anthropometric data of lengths and circumferences of residual limbs of TTA patients. The anterior pad consists of 150 pressure sensors (6x25 rectangle) and is long enough to be folded over the distal end of the residual limb. The posterior pad consists of 175 pressure sensors, where the proximally located part is wider (15x5 rectangle) than the distally located part (10x10 rectangle), to better envelope the upper shin (Fig. 1). The sensors sample at 19Hz and have a capacity of ~700kPa. The pressure-sensing surface mats are placed between the prosthetic socket and the residual limb of TTA patients.

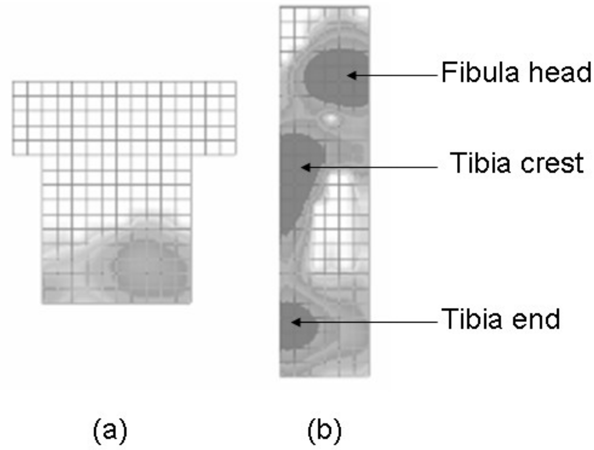

Fig. 1: Pressure distribution recorded during load-bearing by (a) the posterior mat and (b) the anterior mat, folded at the distal end of the residual limb.

In order to calculate internal stresses and strains in the muscle flap of the residual limb, a three-dimensional (3D) patient-specific non-linear FE model is created according to MR images of the individual. The images (with thickness of 4mm) are acquired in an open-MRI setting, while the patient is standing (fig. 1a). The residual limb is inserted to a plastered socket, created pre-trial. Thin force sensors (FlexiForce, Tekscan Co. MA, USA) were used to measure the force applied to the socket during load-bearing. The residual limb is scanned after donning of the plastered socket, first, when no external load is applied, and second, during partial weight-bearing (Fig. 2b). Subsequently, a 3D model of the geometry of the residual limb is developed (Fig. 2c) according to the MR images of the unloaded residual limb, by segmenting tissue types in commercial solid modelling software (SolidWorks, 2005) and importing the data to a FE solver (ABAQUS Inc., Version 6.6). The model is then meshed mostly by second-order tetrahedral 10-node elements, which represent the muscle, fat and skin tissues. The bones are assumed to be rigid bodies. Mechanical properties of the soft tissues are adopted from our previous studies. Specifically, muscle, fat and skin tissues are assumed to be pseudo-incompressible, non-linear materials that undergo viscoelastic stress relaxation under the constant deformation caused by bone compression. The displacement of the truncated bones in relation to the socket is measured on the MR images of the load-bearing trial and used as displacement boundary conditions in each patient-specific FE analysis. Contours of the deformed tissue under the truncated bones, scanned in the open-MRI during the load-bearing experimental phase, are compared to the tissue deformations calculated by the FE software for the purpose of model validation.

RESULTS

Data recorded from the pressure-sensing mats, placed in a the socket of a 31 years old female traumatic TTA patient, revealed high surface pressure around the fibula head (up to 90kPa), tibia crest (up to 100kPa) and tibia end (up to 90kPa) (Fig. 1). Surface pressures at the posterior pad were more evenly distributed and therefore much lower (up to 40kPa). Using the patient-specific FE modeling method described above, we were able to calculate the distributions of stresses and strains in muscle and fat tissues of the residual limb after donning of the socket and during load-bearing (Fig. 2d).

DISCUSSION

In this study, we used Open-MR imaging coupled with FE modelling to calculate patient-specific deep muscle and fat stress and strain distributions after donning of the prosthesis and during load-bearing in TTA patients, *in vivo*. This is the first study to quantify internal mechanical conditions in the residual limb.

CONCLUSION

We conclude that characterization of the mechanical conditions that develop in the internal soft tissues of the residual limb of TTA patients can be fully quantified using MR images and coupled FE analyses. Quantification of stresses and strains in the residual limb, when combined with previous knowledge of the biological response of muscular tissue to transversal loading, can broaden our knowledge of DTI aetiology.

REFERENCES

[1.] Black JM, Adv. Skin. Wound. Care., 18, 415-421, 2005

[2.] Portnoy S, Yarnitzky G, Yizhar Z, Kristal A, Oppenheim U, Siev-Ner I, Gefen A. Ann. Biomed. Eng., 35, 120-135, 2007

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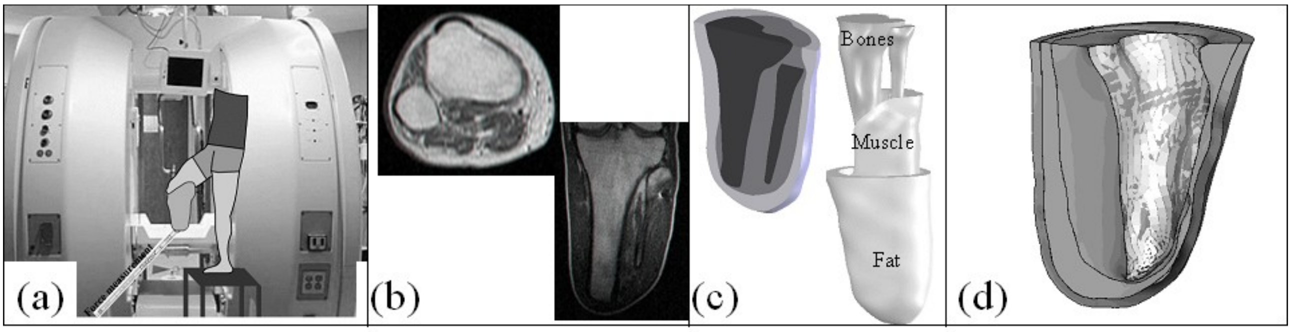

Fig. 2: (a) The residual limb of the TTA patient is placed inside a plaster socket and MR images are taken during standing in an open-MRI with and without applying load. (b) Sagittal and transversal MR images of a TTA patient. (c) The corresponding three-dimensional solid model and (d) stress analyses results (ABAQUS).