Deep Tissue Injury in skeletal muscle: correlation between tissue damage and internal strains as studied by MR tagging, T2-weighted MRI and FE modeling

A. Stekelenburg[1], K. K. Ceelen[2], J. L. Mulders[1], G. J. Strijkers[1], C. W. Oomens[2], F. P. Baaijens[2], and K. Nicolay[1]

[1]Biomedical NMR, Department of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, Netherlands, [2]Department of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, Netherlands

Introduction

Pressure ulcers are localized areas of tissue necrosis that can develop when soft tissues are compressed between a bony prominence and an external surface for a prolonged period of time. They can start at the skin layer or from within the deeper tissues. The latter are termed deep pressure ulcers and they include deep tissue injury [1]. Especially spinal cord injured (SCI) patients are at risk for developing deep pressure ulcers. Indeed, for SCI patients, the occurrence of pressure ulcers is among the most common long-term secondary medical complications. The underlying mechanisms are poorly understood. Prolonged ischemia is the most adhered explanation, but more recently the role of large deformations in the onset of tissue damage was suggested [2]. In the present study the correlation between the location of tissue damage and the location of high strains was investigated using MRI techniques and finite element (FE) modeling. The FE model was validated by MR tagging experiments.

Methods

To study the underlying mechanisms of deep tissue injury an animal model [3] was used in which the tibialis anterior muscle (TA) of Brown Norway rats is loaded with an indenter for 2 hours (n=9). The loading of the muscle was performed inside a 6.3 Tesla MR scanner which allows measurement of the exact deformation of the muscle (figure 1a and b). The tissue damage after unloading was measured using T2-weighted MRI and the deformation and internal strains by MR tagging. T2-weighted MRI and MR tagging could, however, not be combined in a single experiment since tagging experiments require fast repetitive indenter applications, which inevitably causes damage and swelling of the tissue. Therefore, a dedicated FE model was developed to simulate experiments to be able to assess internal tissue strains. This model was validated using MR tagging experiments (n=4). If the predictions of the model in terms of deformation are accurate enough, dedicated FE models may be used to correlate damage location to high strain regions.

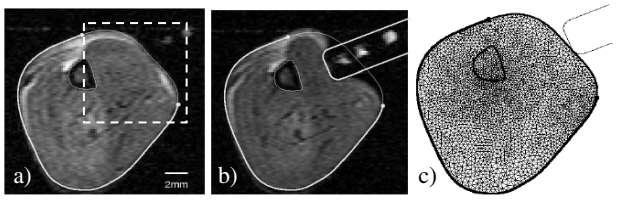

Figure 1: *MR images a) before and b) during indentation and c) dedicated FE model. Dashed square is indicated in figure 3b.*

MR Tagging: Taglines were applied in two orthogonal directions in a transversal slice using CSPAMM (Gaussian RF pulses of 200 µs, gradient strength of 30 mT/m) (figure 2). A T1-weighted gradient-spoiled echo sequence was used to image the tagging grid. The applied method for quantification was the HARmonic Phase (HARP) analysis. **T2-weighted MRI:** A multi-echo spin echo sequence (TE=12-96 ms, 8 echoes, TR=4.5 ms, FOV 30x30 mm^2, matrix 128x128) was used to detect damage. **FE model:** A dedicated 2D plane stress FE model (figure 1c) was developed. Meshes were made with Matlab by detecting the undeformed outer contours (figure 1a). The contour was filled with triangles, which were transformed to extended quadratic triangles. All soft tissues were modeled as a single material with neo-Hookean constitutive material behavior. The model was implemented in Sepran. To compare model and experiment, maximum shear strains τ were evaluated on corresponding positions in the model mesh and the tagging data.

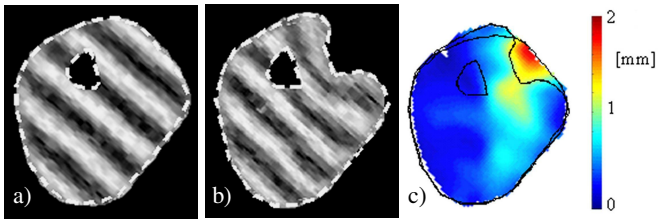

Figure 2 *C-SPAMM images, with tagging grid perpendicular to indentation direction, a) before and b) during indentation. c) Indentation calculated from displacement of tagging lines.*

Results

The deformed contours predicted by the FE model agreed well with the contours of the deformed hindlimbs in the MR images. Figure 3a illustrates the correlation for maximum shear strain τ. Pearson's correlation coefficient was 0.74. To determine whether the correlation between model and experiment is acceptable for the intended use of the model, positive predictive values (ppv) were determined for τ. For all experiments, the ppv decreased for increasing threshold values, but was above 70% for a threshold for τ below 0.5. Based on these results, dedicated FE models were used to correlate the location of damage, as deduced from T2-weighted MR images, to high strain regions. Figure 3b shows that high strain values pixels corresponded with the location of damage (white dots). In figure 3c the relative damage area is plotted against the max shear strain value, illustrating a high correlation.

Discussion

The correlation between strains obtained from MR tagging experiments and from the dedicated finite element model was sufficient for the intended use of the model. To test the hypothesis that large deformations play an important role in the initiation of deep tissue injury, damage location, measured by T2-weighted MRI, was correlated to high strain regions. It was demonstrated that the amount of damage increased with increasing shear strain. This demonstrates the importance of large deformations, besides ischemia, in the etiology of deep pressure ulcers.

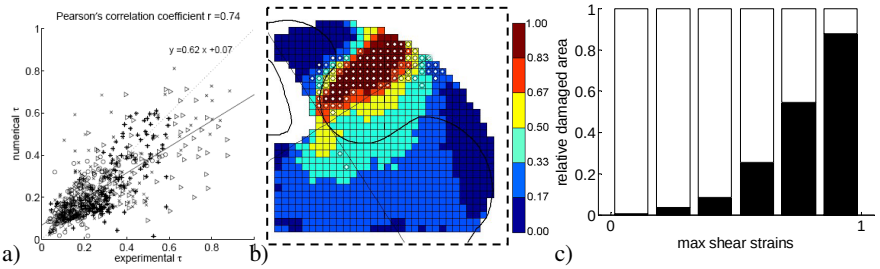

Figure 3 *a) Correlation between numerical and experimental maximum shear strains. b) TA region with calculated max shear strains and damage location indicated by white dots. c) Relative damage area as a function of max shear strain values.*

References: [1] Ankrom et al., Adv Skin Wound Care 18: 35-42, 2005 [2] Bouten et al., Arch Phys Med Rehabil 84(4); 616-9, 2003 [3] Stekelenburg et al., J Appl Physiol 100: 1946-54, 2006