Proceedings of the ASME 2008 Summer Bioengineering Conference (SBC2008)
June 25-29, Marriott Resort, Marco Island, Florida, USA

SBC2008-192779

REAL-TIME CONTINUOUS MONITORING OF SUB-DERMAL TISSUE STRESSES UNDER THE ISCHIAL TUBEROSITIES IN INDIVIDUALS WITH SPINAL CORD INJURY

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INTRODUCTION

Individuals with a spinal cord injury (SCI) are susceptible to deep tissue injury (DTI) which is a pressure-related-necrosis that onsets in the gluteus muscles under the ischial tuberosities (IT). The condition may exacerbate to widespread tissue necrosis and sepsis [1], but early detection is currently not feasible because the injury starts and progresses under intact skin. In SCI patients, local elevated mechanical strains and stresses are formed around the IT, and are not relieved through motion [2]. The excessive tissue strains and stresses, combined with ischemia and hindered diffusion, induce and promote muscle cell death [3]. Recently, we developed a real-time, patient-specific finite element (FE) modeling method and experimental system with a clinical orientation of providing early detection of sub-dermal mechanical conditions that potentially lead to DTI. We presented this system and initial data from healthy adults during the 2006 Summer Bioengineering Conference [4]. Herein, we provide, for the first time, data from trials in an individual with SCI monitored by the system, which indicates that mechanical conditions in gluteus muscles of SCI patients are substantially distinct from those of control subjects.

METHODS

Patient-specific finite element modeling

The real-time FE modeling method was previously described in [4]. To review briefly, a symmetrical, two-dimensional (2D), plane stress FE model of the IT and enveloping soft tissues (skeletal and smooth muscles, fat and skin) is built for each individual based on his/her cross-sectional MRI anatomy (Fig. 1a). The FE code is clinically-oriented and, therefore, it is parametric and allows a definition of the dimensions of the bony prominences as well as the thickness and stiffness of the soft tissue layers of the individual. To allow real-time continuous stress calculations, muscle and fat tissues are assumed to be linear-elastic materials with elastic modulus of 8.5 and 32 kPa, respectively. Poisson's ratios are taken as 0.49 for muscles and as 0.4 for fat. The IT-gluteus interface is at "no-slip" contact. Sitting interface pressures, sampled at 1Hz using a pressure mat (Tactilus, Sensor Products Co.), are fed into the model as real-time pressure boundary conditions. The hardware therefore includes the pressure mat, a connection box with A/D convertors, and a PC laptop that runs the real-time FE software. The system of real-time FE equations is solved continuously by means of this specially developed software using the *LU* decomposition method, which provides the optimal time for solution in a case where only the vector of boundary conditions is changing between multiple solutions [5]. Validation studies of the real-time FE code and system are described in [4,5].

Stress studies in an individual with spinal cord injury

Helsinki approval and informed consent were obtained for the studies. A real-time, patient-specific FE model of the ischial region was built for an individual with SCI (male, age 21 years, bodyweight 90 kg), based on an MRI scan of his buttocks taken while the subject was at a non-weight-bearing sitting-like posture, as described in [2]. After defining the geometry of a cross-section through his buttocks based on the MRI data, as shown in Fig. 1a, the subject was asked to sit normally in his own wheelchair, on a wheelchair cushion (ROHO), and to watch a movie for 90min. Continuous interface pressure measurements were acquired between the patient's buttocks and cushion, by means of the pressure mat. Pressure data were communicated to the PC laptop in real-time for a real-time FE analysis of deep tissue stresses (Fig. 1b). The following outcome measures were extracted from the raw internal stress distributions (Fig. 1b): maximal principal compression stress, tension stress, von Mises stress and shear stress in the gluteus muscles at both sides of the body.

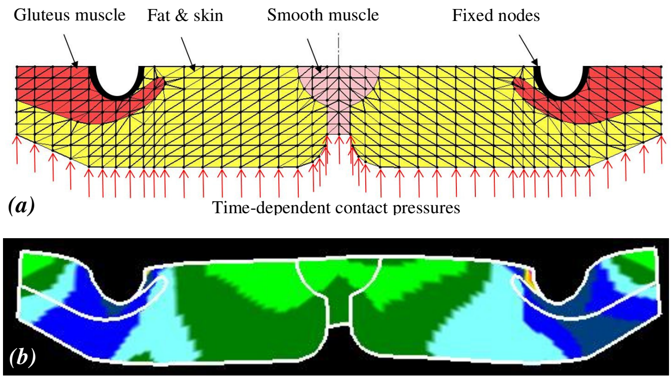

Figure 1. Real-time finite element model of the buttocks of an individual with spinal cord injury: (a) The individual tissue geometry (extracted from MRI) with the corresponding FE mesh and boundary conditions. (b) A distribution of soft tissue compression stress intensities at a certain moment in time during the 90min sitting trial (see Fig. 2 for quantitative data).

RESULTS

Quantitative output of stress-time plots from the real-time FE system is shown in Fig. 2. For our test subject, we found that during a 90min continuous sitting trial, the maximal principal compression, principal tension, von Mises and shear stresses were 32±12, 13±5, 28±10 and 11±4 kPa under the right IT, and 50±17, 21±7, 44±15 and 18±5 kPa under the left IT, respectively (means ± standard deviations; data averaged over the 90min trial). Maximal continuous time exposure to a pressure level above 30kPa (225 mmHg, i.e. nearly double the systolic pressure) was approximately 33min (Fig. 2). A spontaneous pressure relief maneuver of the patient, as recorded by the system, is clearly seen at the 3500s time point (Fig. 2).

DISCUSSION

Our method and system for real-time subject-specific FE analysis of internal tissue stresses [4,5] was presently tested for its utility in continuous monitoring of gluteal stresses under the IT in an individual with SCI during prolonged wheelchair sitting. We found that in our test subject, muscle stress measures under the left IT were substantially and consistently larger than respective measures under the right IT (Fig. 2), despite the assumed symmetry of the buttocks anatomy. This finding, which was not observed in studies of control subjects, strongly indicates the unbalanced sitting posture of the SCI patient in his wheelchair, which is characteristic to the condition. The data provided herein are useful to directly imply from the unbalanced sitting posture to the unfortunate consequences of elevated localized muscle stresses that may eventually cause the DTI. The system was also sensitive to spontaneous postural reliefs, thereby allowing assessment of the real-world stress-time exposure conditions for muscle tissue in the buttocks of SCI patients. Another important issue was that even with the use of a specialized cushion, compression and von Mises stresses were relatively high, above 70kPa (525mmHg, i.e. above 4-fold the systolic pressure) at short episodes (Fig. 2). Last, the exposure time to continuous, non-relieved elevated stresses (above 30kPa) was relatively high, longer than 30min, which is higher than all our corresponding observations in healthy individuals [6]. With further studies, currently undertaken in our lab, this system will be able to provide load-time injury thresholds for humans, which are essential for development of clinical guidelines and protective equipment.

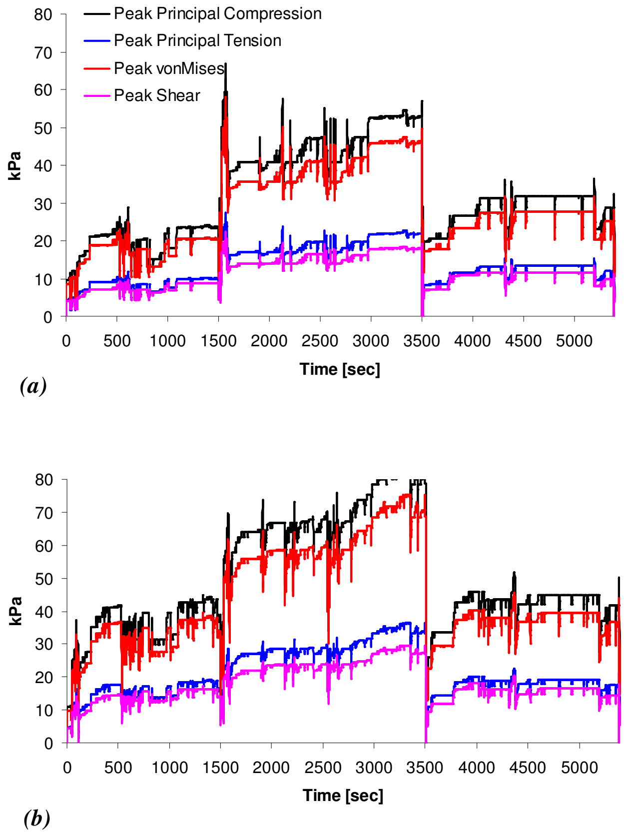

Figure 2. Maximal stresses in gluteal muscle tissue of the buttocks under the right (a) and left (b) ischial tuberosities, calculated in real-time during a 90min sitting trial.

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