REAL-TIME FINITE ELEMENT MONITORING OF INTERNAL STRESSES IN THE BUTTOCK DURING WHEELCHAIR SITTING TO PREVENT PRESSURE SORES: VERIFICATION AND PHANTOM RESULTS

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Abstract. *Deep pressure sores (DPS) in soft tissues of the buttocks are a life-threatening and costly complication in wheelchair-bound patients. Mechanical stress concentrations and excessive deformations in the gluteus muscle under the ischial tuberosities (IT) are associated with DPS onset in these patients. In this study we developed a patient-specific finite element (FE) modeling method that allows visualization and analysis of gluteal stresses/deformations during wheelchair sitting in real-time, based on continuously measured sitting contact pressures. In order to validate our real-time FE method, we built a physical phantom of the buttock. For each posture, measurements (resulting from sensors embedded in the phantom) and calculations (from the real-time FE model) of internal stresses under the left IT were obtained and compared. We found that internal stresses calculated using real-time FE were highly correlated with internal stresses measured by the sensors embedded in the phantom (error: 4 ± 4 KPa, Pearson correlation 0.98). We conclude that our real-time FE method is valid for monitoring gluteal stress concentrations under the IT, and are expecting that this method will make a substantial contribution in preventing severe DPS among chronic wheelchair users.*

1 INTRODUCTION

Pressure sores in deep soft tissues of the buttocks are a life-threatening and costly complication in wheelchair-bound patients. It was reported that 25 to 80% of the patients with spinal cord injury develop pressure sores [1]. Pressure sores are also an important cause of mortality. An estimated 7-8% of all deaths among spinal cord injured patients are due to complications resulting from pressure sores [2]. The costs of treating pressure sores in spinal cord injured patients are substantial, exceeding 1.2 billion dollars annually in the United States alone [3].

Pressure sores range in severity from superficial skin irritation and lesions in subcutaneous and fat tissues to deep muscle necrosis [4]. Two different types of pressure sores are defined in the clinical literature: (i) superficial pressure sores that progress from the skin towards the subcutaneous tissue and muscles, and (ii) deep pressure sores (DPS) that initially developed in deep soft tissues enveloping bony prominences, and progress outwards. DPS are considered as the more severe type of injury [5,6]. This paper focuses on DPS among permanent wheelchair users.

Mechanical stress concentrations and excessive deformations in the gluteus muscle under the ischial tuberosities (IT) are associated with DPS onset [7,8]. Immobilized and neurologically impaired wheelchair-bound patients are particularly vulnerable to DPS due to obstruction or occlusion of blood supply to buttock muscles, by focal internal bone-muscle mechanical stress concentrations [6,8]. Thus, in order to analyze DPS onset with the aim of protecting patients from DPS, the internal stresses and deformations in muscles under the IT need to be measured or calculated during wheelchair sitting. Direct measurement of buttock muscle stresses/deformations is currently not feasible with a non-invasive technique, but computational models can be used for that purpose.

Although several computational models were developed for simulation of the stress state under the IT during sitting [8-10], none of the published models is patient-specific or has the ability of real-time stress/deformation analysis. Hence, none of the published models can be employed as a clinical tool for injury prevention. Moreover, in previous clinical studies that focused on pressure sore prevention [11,12], interfacial pressures between the patients' buttocks and the cushion were measured and reported as a criterion for tissue injury, but the internal stresses/deformations which actually caused the deep tissue injury are unknown. Accordingly, the general goal of this study was to develop a patient-specific finite element (FE) model of the buttock that allows visualization and analysis of gluteal stresses/deformations during wheelchair sitting in real-time, based on continuously measured sitting contact pressures. A specific goal of this paper is to report validation studies conducted with our real-time FE method, to verify that its evaluations of deep tissue stresses/deformations in the buttock are adequate.

2 METHOD

In order to validate our real-time FE tissue stress monitor, we built a symmetrical two-dimensional (2D) real-time FE model of the buttock and a physical phantom of the buttock, both constructed according to MRI section through the pelvis of a seated female (age:29 years, body weight:54 Kg).

The phantom (Fig. 1) contains a pelvic "bone" made of rigid plastic (E=12MPa, υ=0.3), and enveloping "soft tissues" made of silicone (E=1.6MPa, υ=0.49). Six ultra-thin flexible pressure sensors (FlexiForce, Tekscan Co.) were located under the IT of the phantom to measure internal compressive stresses while the phantom is subjected to external loading. Additional 14 sensors were located between the phantom and wheelchair to measure interfacial "sitting" pressures under the IT projections. The phantom was loaded with weights simulating 50 to 90 Kg body-weights in different positions (erect and non-erect, right and left tilt, symmetrical). For each position, a different weight was used and internal compressive stresses and sitting pressures were recorded simultaneously. The internal stresses were used for validation of the real-time FE predictions and the sitting pressures were used as real-time boundary conditions for the real-time FE simulation, as explained later on.

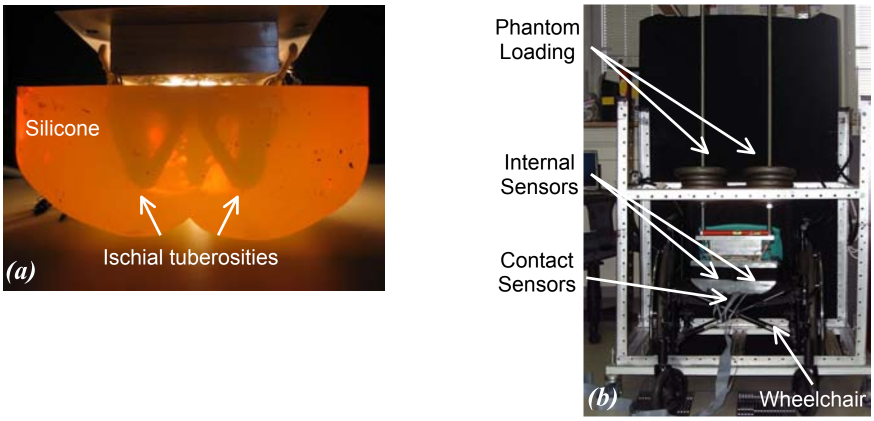

Figure 1: The physical phantom. (a) Pelvic "bone" made of rigid plastic (the ischial tuberosities) and surrounding “soft tissues” made of silicone. (b) The loading set-up of the physical phantom contains the locations of sitting and internal pressure sensors.

A 2D FE model of the IT and enveloping soft tissues that was specific for the cross-sectional MRI anatomy of our female subject (and with geometry that corresponds the phantom) was used for the real-time analysis (Fig. 2). The mechanical properties of the phantom were fed to the real-time FE model, and the IT-gluteus interface in the model was set as "no-slip" (Fig. 2). Sitting pressures were sampled at 4 Hz and fed into the model as real-time pressure boundary conditions. The FE solver utilized LU decomposition to solve the linear set of equations:

$$[S]\cdot\{D\}=\{B\} \tag{1}$$

where [S] is the stiffness tensor of the FE mesh, {D} is the nodal displacement vector and {B} is the measured force boundary conditions vector, measured in real-time by the pressure sensors under the phantom. Symmetrical loading, tilting to the right and tilting to the left (15º) at erect (90º) and non-erect (60º) positions were simulated using our loading apparatus. For each posture, measurements (acquired from the sensors embedded in the phantom) and calculations (from the FE model) of internal stresses under the left IT were obtained (Fig 3.).

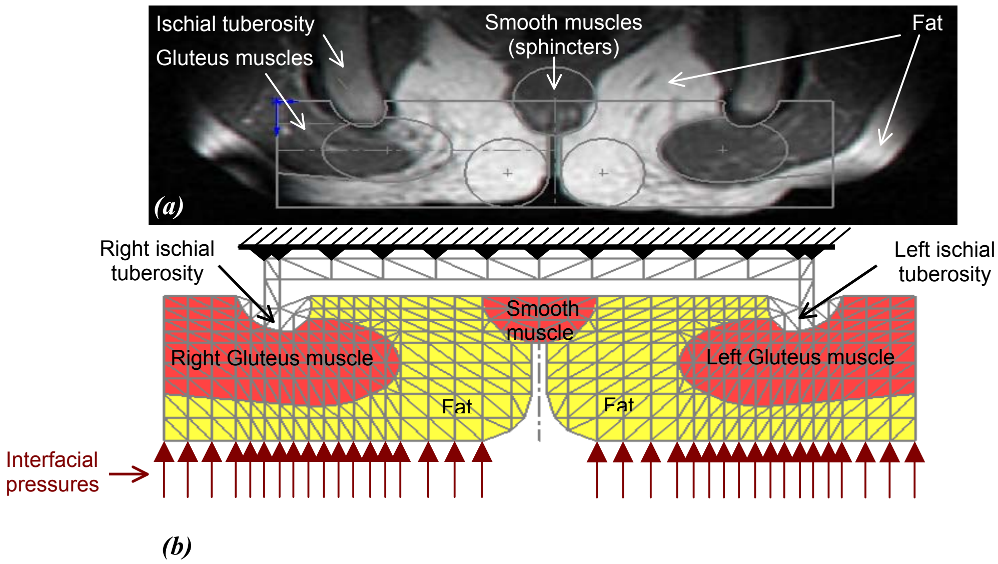

Figure 2: Finite element model. (a) MRI section through the ischium of a seated female, and (b) the FE model contains the gluteus muscles, smooth muscles, fat and bones under the real-time boundary conditions (interfacial pressures).

3 RESULTS

We found that internal stresses calculated using real-time FE (Fig. 3a) were highly correlated with internal stresses measured by the sensors embedded in the phantom (Pearson correlation 0.98, Fig 3b). Importantly, it is shown that data points are generally located close to the unity (ideal agreement) line and randomly distributed above and below it, i.e., the real-time FE model does not consistently overestimates or underestimates measured internal stresses. The mean value of the predictive error of the real-time FE model of the buttock:

$$\frac{\left[\sum \left|\sigma_{MES} - \sigma_{FE}\right|\right]}{N} \tag{2}$$

was 4 KPa, and the standard deviation of the predictive error was also 4 KPa (N=44 experiments). To verify our real-time FE code for numerical accuracy, we compared its calculations with those of commercial FE software (NASTRAN 2003) using the same mesh, tissue mechanical properties and pressure boundary conditions in both analyses, and found differences that were smaller than 5 KPa.

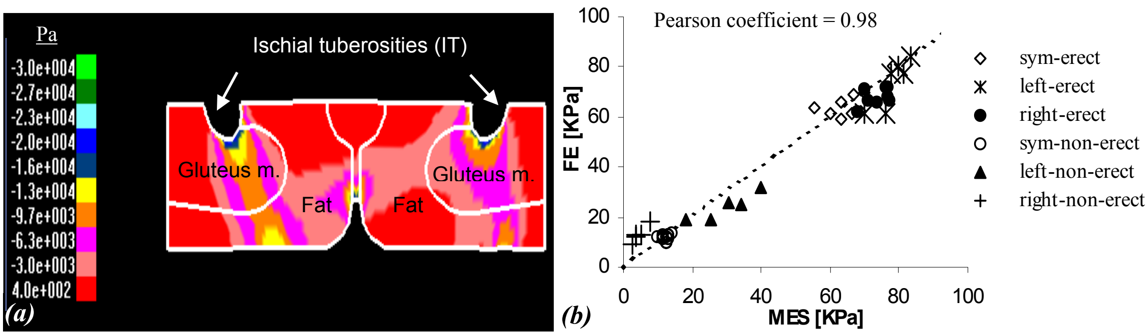

Figure 3: Real-time FE model showing principal compression stresses under symmetrical loading (a), and measured (MES) versus calculated (FE) internal stresses (b).

4 DISCUSSION

We conclude that real-time FE is a valid method for monitoring gluteal stress concentrations under the IT, and are expecting that this method will make a substantial contribution in preventing severe DPS among chronic wheelchair users. Human studies with our real-time tissue stress monitor are now underway at our laboratory to determine the stress magnitudes and time exposures which occur in gluteal muscle tissue during sitting of healthy and wheelchair-bound subjects.

5 ACKNOWLEDGEMENTS

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