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Bone geometry on the contact stress in the shoulder for evaluation of pressure ulcers: Finite element modeling and experimental validation

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ABSTRACT

This research presents the finite element modeling (FEM) of human-specific computed tomography (CT) data to study the effect of bone prominences on contact stress in the shoulder for prevention of pressure ulcers. The 3D geometry of scapula, skin, and surrounding soft tissues in the shoulder was reconstructed based on the anonymous CT data of a human subject in a prone posture (without loading on the shoulder) for FEM analysis of the contact stress. FEM analysis results show that the maximum stress is located at the prominence of the scapula with sharp bone geometry. This demonstrates that stress concentration at the bone prominence is a significant factor to cause the high contact stress, which is a source for pressure ulcers. For experimental validation, a physical shoulder model manufactured by 3D printing of the bone geometry and the mold for molding of tissue-mimicking silicone was developed. Compression tests of the mattress foam and silicone were conducted to find the nonlinear stress–strain relations as inputs for FEM. Experiments of compressing the shoulder model against the foam were carried out. Three flexible force sensors were embedded inside the model to measure the contact forces and compared to the FEM predictions. Results show that the FEM predicted forces match well with the experimental measurements and demonstrate that FEM can accurately predict the stress distributions in the shoulder to study the effect of bone geometry on the inception of pressure ulcers.

1. Introduction

Pressure ulcers (PUs) are localized injuries in deep or superficial soft tissues caused by prolonged and excessive mechanical loading of tissues [1]. PU is particularly common in bony prominent areas with prolonged contact due to the limitation in mobility. In the aging society, PU care is particularly a challenge and represents a tremendous burden to healthcare resources and patients' quality of life. A study by Agam and Gefen [2] showed that PU affected about 10% of hospitalized patients and 5% of community care patients. Park-Lee and Caffrey [3] estimated the annual cost of PUs to the US healthcare system to be more than $1 billion. Numerous wheelchair users and bedridden individuals suffer from PUs [4], particularly in areas such as the head, shoulder (dorsal of scapular), elbow (medial epicondyle), sacrum, pelvis (iliac crest), buttock, heel, and ankles [5]. For PU treatment and prevention, a better understanding of an individual's anatomical characteristics, such as bone prominence geometry and soft tissue layer thickness, and their effects on contact stress, are critical information for personalized PU care. We hypothesize that bone prominences with sharp geometry are the location to initiate PUs and affect the outcomes of contact stress distribution.

Finite element modeling (FEM) has been utilized to study the contact stress in regions prone to PUs [6–13]. Chou and Odell [6], Dabnichki et al. [7], and Oomens et al. [8] developed a 2D buttock model and found that the maximal compressive stress close to the bony prominences depends on surface conditions, the foam in the cushion was critical for stresses at superficial and sub-dermal soft tissue. Linder-Ganz et al. [9–11] developed a sliced 3D buttock model based on the open magnetic resonance imaging (MRI) data, which could distinguish the bone, muscle, fat, and skin. Effects of loading time on the mechanical responses of soft tissues demonstrated that tissue injury onset was affected by postures. Makhsous et al. [12,13] developed a comprehensive 3D buttock model based on MRI data of human subject in a wheelchair sitting posture. The stress and displacement of both superficial tissues and interior muscles at off-loading and normal postures were analyzed and compared to MRI measurements. Besides the buttock model, there is limited FEM analysis in other PU-prone regions based on human-specific geometries. In this study, a 3D FEM shoulder model is selected and developed based on the computed tomography (CT) data to study the contact stress on both superficial and sub-dermal soft tissues.

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One of the key challenges in FEM analysis of contact stress in soft tissue is the validation with experimental measurements. Although the superficial contact stress can be measured and compared to FEM predictions, the validation of internal stress is technically challenging [11]. Makhsous et al. [12,13] and Linder-Ganz et al. [11] utilized MRI to measure the soft tissue deformation around buttock due to loading and compared to FEM predicted deformation. This approach is limited by the resolution of MRI for tissue displacement measurement. Recently, clinical simulator models have been developed for training of medical procedures [15]. Linder-Ganz et al. [14] presented a method to measure the contact stress in a simplified physical buttock model for comparison with FEM analysis. For experimental validation, a new approach utilizing the physical shoulder model will be developed. The anatomically accurate scapular is fabricated by 3D printing and the skin and soft tissues are molded using the 3D-printed mold and tissue-mimicking silicone materials [29]. Force sensors are embedded inside the physical shoulder model to measure the contact force, which is then converted into pressure and compared with FEM predictions.

Another challenge for modeling is acquiring the accurate material properties, particularly the lack of large-strain, nonlinear stress–strain properties of the foam and soft tissues, as inputs for FEM. In this study, we have conducted compression tests of the foam and soft tissue-mimicking silicone materials to derive the stress–strain curves to improve the accuracy of FEM.

The shoulder is a major load-bearing region with high stress and high risk for PU of bedridden patients in the backrest posture [16]. Major muscles surrounding the shoulder control the upper body movements [17,18]. For bedridden patients, shoulder/back are the common sites suffer from PUs on the upper part of the body [32,33]. PU in the shoulder not only causes pain but also affects the normal activities of an individual, thus greatly limits the mobility and quality of life for the patient. Several studies have been conducted to study the force and stress distributions on the scapula [19–21] and muscle [22]. Hadid et al. [23] developed a FEM shoulder model based on the open MRI images to study the mechanical stress and strains in soft tissues during the static load carriage. Linder-Ganz and Gefen [34] studied the mechanical properties of muscles exposed to compression induced PUs in a rat model, and then applied abnormal mechanical properties of injured muscles to the simplified sliced human body parts, including head, shoulder, pelvis, and heels, to characterize consequent changes in the state of tissue stresses. Limited researches have been conducted on the human-specific shoulder model to study the effect of bone prominence and geometry on contact stress and potential locations for the incipient of PUs.

In this study, a comprehensive 3D geometry in the shoulder region of an anonymous human subject in the prone posture is developed based on the patient-specific CT data. This 3D geometry is applied to generate a FEM shoulder model. The contact stresses on both superficial and sub-dermal soft tissues over shoulder region are predicted using the FEM. The bone prominence geometry and its effect on contact stress are discussed. A physical shoulder model, fabricated using 3D printing and embedded with force sensors, is utilized for experimental measurement of contact stress for validation of the FEM.

2. Methods

2.1. Shoulder region geometry based on CT data

A 3D model of the shoulder scapula and surrounding soft tissues was created using the CT data of an anonymous subject (adult female, 72.6 kg weight, 1.83 m height, 21.7 body mass index (BMI)). The sliced distance of the CT images is 0.6 mm and the pixel spacing is 0.938 mm. The prone posture, as shown in Fig. 1(a), provides a no-loading condition surrounding the scapula. Using Mimics® (v15.04, Materialise, Leuven, Belgium), the Digital Imaging and Communications in Medicine (DICOM) data were converted into a series of stacked gray-scale images with each pixel quantified by the Hounsfield Unit (HU). Each type of tissue corresponds to a specific range of HU [15]. In this study, the range of HU for skin is from −45 to 100, muscle is from 60 to 80, and the bone is from 350 to 1450. The scapula, skin layer, and surrounding soft tissue for human-specific shoulder are distinguished, as shown in Fig. 1(b).

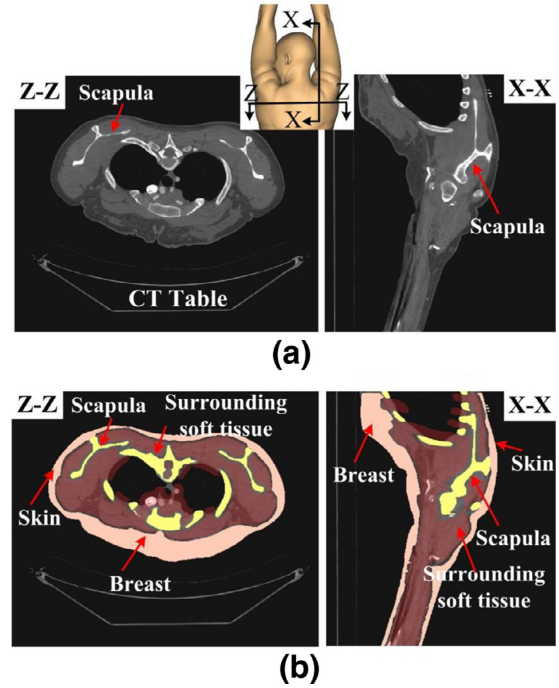

Fig. 1. Human subject shoulder region: (a) CT data and (b) the scapula, skin layer, and surrounding soft tissue.

Using Magics® (v15.04, Materialise, Leuven, Belgium), pixels of the same HU are connected to generate three continuous 3D objects of scapula, skin layer, and surrounding soft tissue (encompassing all underlying layers of muscle and fat). Fig. 2 shows the overview and cross-sectional view of shoulder region. Three surfaces of the scapula (subscapular fossa, infraspinous fossa, and supraspinous fossa) are marked in Fig. 2(c).

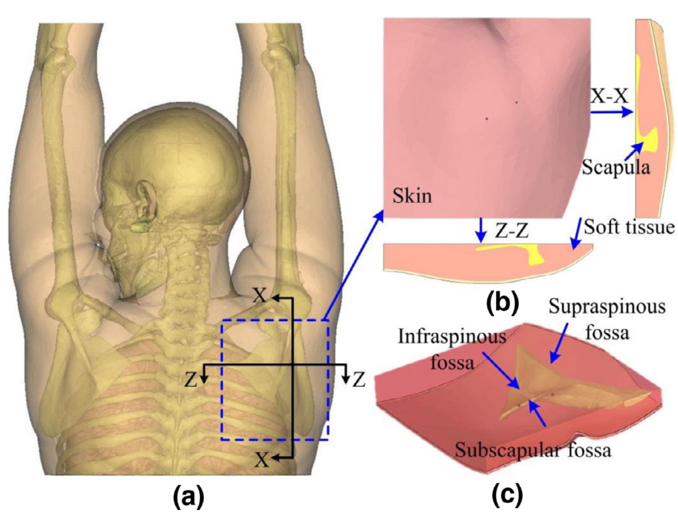

Fig. 2. (a) Transparent view of the 3D shoulder model, close-up views of the shoulder region in (b) cross-sectional and (c) isometric view and three surfaces of the scapula.