Multi-Modal Framework for Subject-Specific Finite Element Model Generation aimed at Pressure Ulcer Prevention

Bucki M., Payan Y., Cannard F., Diot B., Vuillerme N.

Abstract—Biomechanical finite element (FE) modeling of the buttocks soft tissues is essential for an efficient prevention of pressure ulcers. Indeed internal overpressures not only depend on external skin pressures but also on each individual’s morphology. We present a technique for fast and automatic FE model generation using standard and novel imaging modalities.

I. INTRODUCTION

Pressure ulcers represent one of the most common, disruptive, disabling life-threatening conditions affecting persons with spinal cord injury (SCI) and more specifically wheelchair users. Whereas it can take only a few hours for a pressure ulcer to develop, complete healing may require a months’ hospital stay, involving difficult and expensive medical or surgical treatments. Currently available techniques and protocols designed to prevent pressure ulcer formation are mainly based on the improvement of the skin/support interface and on a postural and behavioral education. These techniques however, seem to lack efficiency as the prevalence and incidence of pressure ulcers still remain very high. Development and validation of efficient solutions to prevent pressure ulcers is thus strongly needed.

Until recently, it was thought that deep tissue ulcers stemmed from internal overpressures [1] yet recent results suggest that it is not the internal pressure but the strains that best reflect the level of tissue damage [2]. Unfortunately only external pressures, at the interface between the skin and the cushion, can be measured by the available sensors. Internal strains can however be estimated from the values of external interface pressures by resorting to biomechanical modeling in a Finite Element (FE) modeling framework. A possible prevention strategy consists in continuously assessing the level of tissue damage by means of a biomechanical model subject to loads identical to those measured at the buttocks/cushion interface. However to properly estimate the levels of compression within the subject’s soft tissues, the model must accurately replicate the considered morphology.

This article describes a fast, automatic and robust technique for the generation of patient-specific models to be used within a personalized pressure ulcer prevention strategy. The technique resorts to multiple complimentary modalities to gain insight at the patient’s morphology while maintaining an acceptable benefits/risks (or costs) ratio.

M. Bucki is with TexiSense, Montceau-les-Mines, France (e-mail: marek.bucki@texisense.com).
Y. Payan is with TIMC-IMAG Lab., UMR CNRS 5525, La Tronche, France (e-mail: yohan.payan@imag.fr).
F. Cannard is with TexiSense, Montceau-les-Mines, France (e-mail: francis.cannard@texisense.com).
B. Diot is with IDS, Montceau-les-Mines, France.
N. Vuillerme is with FRE 3405 AGIM Lab., CNRS-UJF-UPMF-EPHE, La Tronche, France (e-mail: nicolas.vuillerme@agim.eu).

II. METHODS

A. Mesh warping: Mesh-Match-and-Repair

To produce high quality personalized FE models it is necessary to resort to medical imaging and acquire the most relevant possible description of the modeled morphology. Yet building a FE model from a medical data set can be a challenging and time consuming task. To overcome the commonly encountered problems – such as partial organ imaging, presence of noise or poorly reconstructed surfaces – a “mesh warping” approach has been chosen for its versatility. In this framework, a generic or “atlas” model representing a typical organ is first assembled. Then, for each patient the atlas model is warped, or registered, so that its shape accurately represents the target morphology. We refer the reader to [3] for further details on this topic.

Among the many “mesh warping” techniques Mesh-Match-and-Repair (MMRep) [3] was chosen to perform this task. The atlas FE model was assembled using the Zygote (Zygote.com) data base. As internal overstrains tend to develop near bony prominences the shape of the pelvis – and most importantly the ischia and sacrum – must be accounted for in the model. Furthermore given the difference of stiffness between fat and muscle tissues the corresponding regions should be differentiated within the model. Consequently, the atlas model used here comprises: pelvis (iliac bones and sacrum), femurs in seated position, skin surface and inner fat/muscle interface. MMRep is a four steps process. First the patient data is registered onto the atlas. In this case, the patient’s skin surface is fitted onto the atlas model skin. This “direction” is dictated by the formulation of the registration criterion and the fact that medical data available for a given subject usually represents a subset of the atlas data. Second, the resulting deformation is inverted in order to operate from atlas to patient frame. Thirdly, the deformation is applied to the atlas FE nodes (elements connectivity remains unchanged), bone model and fat/muscle interface. As the non-linear deformation is computed based solely on the patient skin surface, the position of the inner structures is only a reasonable approximation of the actual patient’s morphology.

Finally, the registered FE mesh must undergo a repair procedure in order to untangle some of the elements that might have undergone excessive deformation. The goal of mesh repair is to recover “validity” for all mesh elements (an invalid element makes FE analysis impossible) and enhance element “quality” (poor quality elements affect the numerical accuracy of the FE analysis). For a mathematical discussion on FE mesh repair we refer the reader to [4].
B. Multi-modal morphology acquisition

An economically acceptable and practical image acquisition workflow must be designed in order to make personalized biomechanical modeling available for the largest number of wheelchair-ridden persons. We propose to use three different modalities providing an increasing insight at the subject’s anatomy.

1. **Kinect (Microsoft).** This 3D surface scanner makes it possible to acquire within minutes the skin surface of the subject’s buttocks. It is low-cost, easy to operate and does not present any risk for the subject. Two sensors are used in this device: a color camera and an infra-red (IR) camera. The VGA color camera (CMOS) has a 640x480 resolution with a frame rate of 30Hz. The IR camera (1600x1200) has a 640x480 depth map resolution. This camera captures data from an IR laser projector emitting through a diffraction grating. The Kinect field of view is 43° vertical by 57° horizontal, from 40cm to 400cm. The “Reconstructme” software (Reconstructme.net) working with the Kinect device is used to convert depth map data into 3D triangular surface meshes. Only the outer shape of the buttocks can be recorded using this modality.

2. **EOS bi-plane X-Ray imaging.** This novel modality performs a full body scan with a radiation dose between 2.9 to 9.2 lower than a traditional X-Ray image [5]. The output is a 1764x9616 sagittal image and a 1896x9616 frontal image for a 1.72m high subject both with a pixel size of 0.18x0.18mm. A very good contrast between soft and hard tissues permits the reconstruction in 3D the shape of the pelvic bones (iliac and sacrum) [6]. The interface between muscle and fat tissues can also be clearly seen although no 3D reconstruction is available at this time. EOS imaging gives insight at the layout of the internal structures and parameters of interest, namely: the shape of the ischia and sacrum, as well as muscle and fat layer thicknesses.

3. **CT imaging.** Traditionally used to investigate hard tissues, CT also makes it possible to visualize significant soft tissue interfaces such as the muscle/fat boundary. In our application, it is not complimentary to the two previous modalities as it is self-sufficient: both the skin surface and internal structures can easily be reconstructed from a quality CT scan. Nevertheless CT imaging is a lot more expensive than EOS and Kinect and exposes the patient to a radiation dose that may not be justified in the context of pressure ulcer prevention.

C. Model personalization

For each subject, the set of medical images and surfaces is aligned with the atlas model using a set of 6 anatomical landmarks: left-anterior, left-posterior, right-anterior, right-posterior ischial spines, along with left and right trochanters (Fig. 1). Trochanters are secondary landmarks as they lie on the femur and are not directly positioned on the pelvis. Yet, being close to the hip rotation axis their position retain some stability and provides useful information as discussed below. For the atlas, the landmarks are defined at atlas model assembly stage once and for all, and for each patient the landmarks are manually localized in each modality:

1. **Kinect scan.** Prior to surface scanning, the spines and trochanters are manually palpated and marked on the patient’s skin using small plastic markers. Once the 3D surface reconstructed from the scan, the clearly visible markers are ‘mouse-clicked’ using in-house software.

2. **EOS.** The same type of markers is used. The position of each marker in the EOS 3D referential is found by identifying both sagittal and frontal projections of the considered marker. In-house software is also used to perform this ‘bi-planar picking’ task.

3. **CT.** The same markers are used and manually localized in the volumetric CT image using similar in-house image processing software.

![Figure 1. Anatomical landmarks (green) used to co-register patient data](image)

Once these common fiducials defined, the fully automatic model personalization process begins. First an Arun [7] rigid registration computed on the set of 6 landmarks brings all patient data into the atlas reference frame. Immediately follows a linear fit between patient and atlas landmarks which compensates for most of the scale differences between patient data and atlas model. Finally, the patient specific FE model is obtained by applying the MMRep non-linear deformation and mesh repair procedure on the available patient data, as described in §III.

D. Personalized pressure ulcer prevention strategy

Let’s take a step back and look how this modeling process fits into a larger pressure ulcer prevention scheme. To ensure a daily and personalized prevention the wheelchair-ridden person is equipped with a TexiSense (www.texisense.com) pressure sensing mat placed over the wheel chair cushion [8].

![Figure 2. Overview of the TexiSense pressure ulcer prevention device](image)

The pressure mat is coupled with the subject’s own biomechanical model to which the normal pressure values recorded from the sensor are applied as external loads to simulate the tissues deformation in the current seating posture while the bones in the model remain fixed. Once these
boundary conditions applied, Finite Element analysis is carried out by an on-board micro controller [9] and strain levels in predefined region of interest – below ischia and sacrum – are continuously monitored. Should an excessive deformation of the tissues put the integrity of the tissues at risk, a warning is sent to the user or to the medical staff through a wireless connection (Bluetooth) using a vibrotactile modality (vibrating watch) or a more explicit representation of the situation at risk, through e.g. the graphical display of a smartphone or tablet (Fig. 2).

III. USE-CASES

A. Kinect scan alone

In this lightweight scenario only the skin surface of the patient is acquired and biomechanical modeling solely relies on the estimation of the internal structures provided by MMRep. Kinect scanning usually encompasses more than the body section of interest (Fig. 3a). The patient skin model must thus be clipped prior to registering it onto the atlas skin model so that only the relevant seating area is retained in the model. Fig. 3b shows the clipped patient skin model along with the atlas FE mesh (wireframe). Clipping is done automatically using 2 clip planes built upon the 6 anatomical landmarks: 1) a least squares plane built on the 4 spines and, 2) an anterior plane built on the anterior spines and trochanter points (used mainly to define the cranial-caudal axis). The clipped surface is then registered onto the atlas skin and the patient-specific biomechanical model is produced as discussed in §II.A. Fig. 3c shows the patient FE mesh (wireframe) along with the inferred pelvis, femurs and muscle volume (solid region underneath the trochanters). Fig. 3d shows the patient model with the initial skin surface.

![Image](image_url)

Figure 3. Kinect-based FE model generation (sagittal view)

B. Kinect scan and EOS

The assembly of an accurate biomechanical model requires more than the shape of the skin surface alone. To this end, the external data provided by the surface Kinect scanner can be completed by the shape of the pelvis retrieved from EOS biplanar radiography. The 6 anatomical landmarks discussed above are identified in the EOS slices and used to register the reconstructed 3D pelvis model [6] with the patient skin obtained from the process described in §III.A. Now, instead of being approximated by MMRep, the actual shape of the pelvis can be “imported” into the patient’s model. At this point in the development of the EOS technology, no muscle surface reconstruction is available. In this scenario, the biomechanical modeling of the muscles has thus to rely on the interface estimated by the MMRep deformation.

C. CT scan

The use of this modality is mainly planned for validation purposes, to assess the accuracy of the multi-modal Kinect + EOS reconstruction. The patient is positioned in lateral decubitus in the scanner so as to acquire a nearly unconstrained shape of the buttocks soft tissues on the patient’s upturned side. The lower half of the buttocks being compressed by the weight of the patient, the soft tissue shape that it provides is not relevant for our purpose. Bone, skin and muscle surfaces are segmented from the CT volume using the Amira software. A sagittal quasi-symmetry plane [10] is computed based on the pelvis shape and a complete “unconstrained” buttocks dataset is reconstructed by replacing the lower half of the CT data image, reconstructed muscle and skin surfaces as well as (manually segmented) anatomical landmarks by the symmetrical of their upper half counterparts. Once skin surface clipping carried out, atlas FE model registration is performed using the skin surface as described in §III.A. Pelvis modeling is done the same way as for EOS. Finally element labeling is performed based on their position with respect to the actual muscle/fat interface.

IV. RESULTS

A. Atlas model

The atlas FE mesh was produced using a hexahedral dominant meshing technique [11] and comprises 14,868 elements (8,052 hexahedrons, 2,554 pyramids, 2,534 tetrahedrons and 1,728 prisms). The pelvis and femurs are considered as fixed rigid bodies. The mechanical behavior of the fat and muscle tissues is modeled as an elastic Ogden material with parameters taken from [12], i.e. fat: \( \mu=0.01\text{MPa}, \alpha=5 \); and muscle: \( \mu=0.003\text{MPa}, \alpha=30 \). Skin is not modeled as a distinct material.

B. Model personalization using Kinect and EOS

The accuracy of the Kinect device was initially assessed on spheres of known radius [13]. A mean error of 1.44 and a max error of 4.16mm were obtained. Considering this accuracy acceptable for our application, the shape of the buttocks in 3 subjects was acquired after the 6 anatomical makers have been placed on the skin. The Kinect scan and surface reconstruction took approximately 2 minutes. Manual identification of the anatomical landmarks on the reconstructed skin surfaces was done in less than 30 seconds. Then an EOS scanner was used to reconstruct the shape of the pelvis so as to represent the actual bone shape in each personalized FE model. Finally each model underwent the mesh untangling process making it suitable for FE analysis in the ANSYS software. In all three cases, a subject-specific biomechanical model could be produced within 20 minutes. The only manual intervention was the identification of the anatomical landmarks on the Kinect skin surface and in EOS images which altogether took less than 5 minutes. Skin representation mean error was less than 1mm in all cases.
C. Personalized Finite Element analysis

ANSYS was used to run preliminary tests on the biomechanical models. Fig. 4 shows an axial view of a typical strain map resulting from the application of a sample pressure map recorded by the TexiSense pressure mat. The slice shown in Fig. 4 is placed vertically (considering a seated subject) and cuts through the lower tip of the ischia (red ellipses). Left, right, anterior and posterior sides of the patient are indicated by capital letters.

![Strain map under the ischions](Image)

Figure 4. Strain map under the ischions (lighter blue: higher strains)

The deformation was simulated assuming large displacements and large deformations. The computation time was about 5 minutes on a standard desktop computer.

V. DISCUSSION AND FUTURE WORKS

A framework for multi-modal generation of patient specific biomechanical models of the buttocks has been presented. This framework addresses the need for fast, automatic and robust model personalization in the context of pressure ulcer prevention for the wheelchair-ridden persons. It is also accurate as the representation error measured on the skin is less than 1mm and the pelvis, whenever available in the medical images, is modeled within its segmentation accuracy. The framework furthermore takes into account restrictions on the availability of medical images in situations where the benefits of the ulcer prevention strategy are deemed insufficient in regard of the imaging costs or incurred radiations. Indeed, a low-cost and radiation-free scenario based on a publicly available device (Microsoft Kinect) is proposed although resorting to it results in approximations and loss of accuracy. The effects on the prevention strategy of the approximations in the biomechanical model when no medical imaging of the internal structures is available are currently under study and will be published once a sufficient corpus of “ground truth” CT exams has been collected and processed.

CT imaging itself presents many challenges. First, imaging subjects with spinal cord injury is not a trivial task from a practical point of view, especially when a seating reference position is attempted to be reproduced. Second, it is difficult to obtain a strictly unconstrained shape of the buttocks as it is highly affected by the effects of gravity. Using surfaces extracted from a CT exam to personalize a FE model thus also involves approximations.

Finally computational complexity remains an important challenge as the prevention algorithm will eventually run on a small microcontroller having only a fraction of the CPU power found in the currently used desktop. Yet many options can be foreseen to achieve this goal, among which the use of a “tangent” linear FE model where a set of elementary deformations are precomputed and, once the device installed, linearly combined in real-time based on the measurements of the TexiSense mat to give an instant estimation of the tissue deformation. A preliminary study of this technique has shown promising results [14].

The individual biomechanical modeling technique presented here will undergo validation on a large number of cases as part of an epidemiologic study carried out on 90 wheelchair users followed through 2013.

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CONFLICT OF INTEREST

Some authors are involved with the TexiSense Company (http://www.texisense.com/home_en).

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