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Development of a model to demonstrate the effects of friction and pressure on skin in relation to pressure ulcer formation

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ABSTRACT

Pressure ulcers are a common injury of the skin which leads to pain and potential infection for patients and financial burden to the healthcare providers across the global due to treatment costs, litigation and extended hospital stays. The current study focuses on one of the causes of pressure ulcer formation, ischemia. Blood vessels are deemed to be deformed and blood flow restricted when skin is subjected to external mechanical loads including friction, pressure and the combination of both. Hence, normal oxygen delivery to cells or metabolic waste removal are locally stopped which causes cells deaths and ultimately pressure ulcers.

The current study proposes a 3D finite element analysis model which is capable of demonstrating the effect of friction, pressure and the combination of both to the deformation of blood vessels. The results of simulation suggested that applied pressure collapsed the blood vessels while friction opened up the blood vessels. However, as a combination effect of pressure and friction, the cross-sectional areas of blood vessels were reduced significantly. This model is clinically and physiologically relevant in terms of loading regime and blood vessels structures. The model with further development can be adopted to be an effective tool to evaluate the effects of medical devices to the possibility of pressure ulcer formation.

1. Introduction

The aim of the study is to develop a Finite element analysis (FEA) model to predict the effect of friction and pressure on skin in relation to pressure ulcer (PU) formation. There are two main reasons which are known to increase the possibility of PU formation; ischemia and excessive amounts of internal strain resulting in deep tissue injury [1,2]. The current study focuses on the condition of ischemia resulting from external friction and pressure. Skin and soft tissue becomes distorted when external friction and/ or pressure are applied to skin surface, this results in compression of the blood vessels. This phenomenon has a physiological effect restricting blood flow, with the restriction in blood flow, perfusion of oxygen is limited and removal of metabolic waste is inhibited which leads to cells death in the affected area resulting in ischemia followed by PU formation [3,4]. The proposed model in the current study demonstrates the effect of friction and pressure to the reduction of cross-sectional areas of blood vessels in the different layers of skin including the dermis and hypodermis. This initial model is simplified and the skin is modelled to be isotropic and non-viscoelastic. These initial simplified models are clinically and biologically relevant in terms of skin and blood vessels structures. The loading conditions have been developed by conducting pressure mapping of support surfaces with healthy volunteers in a clinical setting to ensure validity of the loading regimes used. It is proposed that this model with further development could be used to predict the effects of medical devices on the change in blood vessel dimensions whilst indicating the probability of PU formation.

Skin is the biggest organ and often not given the attention that it deserves as one of the most important. It serves to protect the internal organs, prohibit external hazards affecting the body, regulate temperature and absorb shocks. The stratum corneum, epidermis, dermis and hypodermis/ subcutaneous fat are the key layers of the skin Fig. 1. Each of these layers is unique, with different mechanical properties and varying distribution and configuration of blood vessels. This versatile organ can be subjected to various injuries and trauma, one severe instance which causes loss of integrity in the skin as a barrier to bacteria and infection is pressure Ulcers (PU) and friction blister formation.

Pressure ulcers are a skin injury that used to be labelled as "bedsores" or "pressure sores". They can be just a minor

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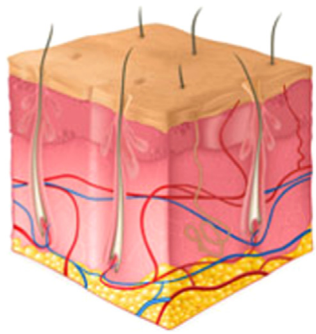

Fig. 1. Diagram of skin structure [5].

discolouration to the skin or potentially life threatening full thickness skin damage affecting all layers from the epidermis to the muscles or even through to the bone. PU usually occur at areas of bony prominence, for instance, the elbow, heel and back of skull. Multiple mechanical parameters including friction, shear stress, pressure and microclimate are believed to be included in the potential triggering factors [6,7].

An increasing trend of PU formation is a financial burden to the healthcare systems across the globe. Treatment cost of pressure ulcers increased from USD 1.3 billion in 1998 to USD 11 billion annually in 2014 in the United States [8–10]. The yearly treatment cost for PU was £1.4 – 2.1 billion in the UK and USD 1.6 billion in Australia [11,12]. The mean cost of treating a pressure ulcer is estimated as £1,214 for stage one ulcer up to £14,108 for stage four [13]. It is more cost effective to prevent the occurrence of ulcers than provide treatment especially for the stage four ulcer [14,15]. According to the NHS information, "Under half a million people in the UK would develop at least one pressure ulcer in any given year" [16]. 11% of the total residents in US nursing homes developed pressure ulcers [17]. These statistics alone demonstrate the urgent need to provide information and development tools which can help clinicians address this global issue.

Furthermore; pressure ulcers are not only a financial burden to the healthcare system but also have the potential for serious impact to patients' health. The increasing trend of pressure ulcers was shown in the study conducted by Russo in 2008. There was only a 15 percent increase in total numbers of hospitalisation throughout the population. However, the number of pressure ulcers developed during the hospitalisation increased 78.9 percent from 281,300 to 503,300 from 1993 to 2006 in the United States [18]. Patients were shown to be restricted and limited in their social and leisure activities and psychologically impaired, especially for prolonged ulceration over six months in duration. Pain from PU was always neglected or unrecognised while pressure-relieving mattresses and cushions were reported to be uncomfortable, too hot, and noisy. Patient's quality of life was lowered by all these factors [19]. Worse still, PU can be fatal and life-threatening in some cases where cellulitis, blood poisoning, bone and joint infection, necrotising fasciitis and gas gangrene developed as a result of PU formation [20]. All these are the possible consequences of untreated stage 3 or 4 pressure ulcers.

The pressure ulcers occur usually as a result of self-weight, for instance, the weight of foot acting on the heel. However, another type of pressure ulcers are labelled as medical device related (MDR) pressure ulcers is of growing concern. Hospitalised patients often require medical devices or other interventions to treat or monitor their physiological conditions. These devices are usually attached to the patient's body with tapes or other fixing methods in order to function correctly. Pressure is often applied to the skin as a result of these fixation methods and some patients cannot even detect discomfort due to unconsciousness, drug therapy or lack of sensations. The medical device on the skin also acts like tourniquet which restricts the blood flow and increases the possibility of pressure ulcers formation [20]. There is also the potential for heat and moisture development at the skin-device interface, this is often referred to as the micro-climate, this refers to the environment and conditions in the surrounding area of direct contact. Out of the total number of pressure ulcers, one third of them were shown to be related to medical devices in a study conducted by Black [21].

A number of studies have been conducted by other authors investigating modelling as a tool to investigate the behaviour of skin incorporating external mechanical or biological factors and other skin injuries [22–24]. However there is little evidence to show the use of three dimensional computational modelling of skin incorporating the structures of blood vessels to demonstrate the effect of mechanical loading typically friction and pressure to PU formation.

2. Method

Finite element analysis (FEA) is a conventional computational method of demonstrating stress, strain and deformation of a model in various disciplines. FEA has been adopted as the analysis method for the behaviour and deformation of skin and blood vessels under friction and pressure, the primary aim being to investigate the use of FEA in the prediction of pressure ulcer formation. Abaqus CAE 6.14 was utilised to conduct the simulation.

In a study by Xu in 2011 FEA was used to simulate the material deformation following nano-indentation of a large block of material, there are some similarities in this method with the study of pressure ulcer formation as the loading contributes gradually less effect on the surrounding are moving away from the point of peak pressure [25]. In the current study the method is focussed less on the deformation of the skin layers and more on the reduction in cross sectional area of the blood vessels within the layers of skin with a view to investigating the reduction in potential blood flow in the areas of high pressure.

2.1. Features of the model

For the purposes of modelling the deformation in blood vessels, the model was created in the micrometre scale. The skin demonstrated by the computational model was circular, however the computational model was presented as a quarter as it was symmetrical in X and Z directions. The model was partitioned into 9 unevenly spaced radial sections with the total radius of 20,600 μm as shown in Fig. 2(a). These sections are label as Section 1 to 9 from centre to the outermost section. The important feature of the model was the blood vessels located at the centre of the model, and the boundary of the model was designed to be a large distance away from the centre in order to have minimum effect to the deformation of affecting the blood vessels in the central region. Iterative simulations demonstrated that 20,600 μm was an appropriate dimension for the boundary conditions. The stratum corneum, epidermis, dermis and hypodermis were the four vertical layers of skin modelled as shown in Fig. 2(b).

2.2. Internal features (Blood vessels) of the blood

Nine horizontal blood vessels were constructed inside the centre section of the model. Two vessels were located at the dermis layer and one of those was near the epidermis while another one was near the dermis–hypodermis interface as suggested by Michel Démarchez [26]. Démarchez also mentioned that these two vessels were connected by vertical vessels which transfers blood from the deeper part of the skin to the cells located at epidermis and dermis layer. All the blood vessels are similar but slightly