

Deformation is a Cell “Killer” – Implications for Protecting Persons with a Spinal Cord Injury from Pressure Ulcers

Deformace je „zabiják“ buněk – implikace pro ochranu osob s poraněním míchy před vznikem dekubitů

Abstract

Sustained internal mechanical deformations, strains and stresses in soft tissues during immobile weight-bearing postures (e.g. in bed or in a chair) were identified as a fundamental cause for the onset and progression of pressure ulcers (injuries), particularly of the deep tissue injury type. The sustained deformations in tissues may compromise tissue viability through distortion of cell shapes and internal structures which damages their biological function and eventually causes loss of cell homeostasis, e.g. by causing abnormal transport changes. In addition, the sustained deformations impair blood perfusion and lymphatic flow which suppresses tissue metabolism and lowers tissue pH. This paper reviews some of our published research concerning the effects of sustained deformations on soft tissue viability and function, with a focus on how minimizing tissue deformations should be a goal for maintaining cell homeostasis and tissue integrity in fragile individuals, particularly patients post a spinal cord injury. Specific examples which are covered in this paper concern: (a) The immersion and envelopment of the buttocks by support surfaces (hospital bed mattresses, wheelchair cushions), which determine the exposure to mechanical deformations and stress concentrations in soft tissues near the bony prominences of the pelvis. (b) Biomechanics and physiology of the buttocks tissues while sitting on the toilet for prolonged times, and how such sitting may compromise tissue viability. (c) The adjustability of support surfaces to misplaced medical equipment in the context of medical device-related pressure ulcers.

Souhrn

Trvalá vnitřní mechanická deformace, namáhání a napětí v měkkých tkáních v dlouhotrvající poloze a postavení u imobilních osob (např. v lůžku nebo na židli) byly identifikovány jako základní příčiny vzniku a progresu tlakových, dekubitálních vředů (poranění), zejména hlubokého poškození tkání. Dlouhotrvající tlak a deformace ve tkáních vedou k narušení a ohrožení vitality tkáně prostřednictvím změny tvaru buněk a jejich vnitřních struktur a poškozením jejich biologické funkce. Nakonec způsobují ztrátu buněčné homeostázy, např. způsobují abnormální transportní změny. Kromě toho, dlouhotrvající deformace zhoršují krevní perfuzi a průtok lymfy, čímž je ovlivněn fyziologický metabolismus tkáně a snižuje se pH tkáně. Tento článek se zabývá některými publikovanými výzkumy týkajícími se účinků trvalé deformace na vitalitu (životaschopnost) a funkci měkkých tkání, se zvláštní pozorností na to, jak minimalizovat tkáňové deformace, což by mělo být cílem k udržení buněčné homeostázy a integrity tkání u křehkých a ohrožených jedinců, zejména pacientů po zranění míchy. Konkrétní příklady, které jsou předmětem tohoto dokumentu, se týkají: (a) ochrany hýždí podpůrnými plošnými materiály (matrace na nemocničních lůžkách, polštáře invalidních vozíků), které určují expozici mechanickým deformacím a koncentracím napětí v měkkých tkáních v blízkosti kostních prominencí pánve; (b) biomechaniky a fyziologie hýžděových tkání, v situacích, kdy postižený sedí po delší dobu na toaletě, a zejména to, jak může takové sezení ohrozit vitalitu tkání; (c) úpravy opěrných a styčných ploch rizikových pro vznik dekubitů v souvislosti se zdravotnickými prostředky a přístroji.

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Introduction

Current aetiological research has identified sustained tissue deformations as the primary cause of pressure ulcers (also termed pressure injuries), both at the skin and in deeper tissues. The chronic exposure to tissue deformations has multi-dimensional influence on tissue health and cell viability, including direct damage to cells (e.g. plasma membrane and cytoskeleton failures), compromised perfusion and lymphatic function [1,2]. Different model systems, including cell cultures, animal models, tissue engineered constructs and medical imaging of humans [2] indicated together that the keys for prevention are:

1. Minimizing exposures to sustained tissue deformations, which allow cells to be structurally and functionally viable, enables perfusion/repair and facilitates clearance of metabolic by-products.
2. Ensuring that the minimization of tissue deformations spans across the entire volume of tissues, from superficial to deep, which would protect the skin but also, importantly, reduce the risk for deep tissue injuries [2].
3. Using biomarkers to ensure that the specific intervention to minimize tissue deformations is effective and indeed, no tissue damage onsets/develops – either superficially or sub-dermally. There are different approaches in achieving minimal exposure to tissue deformations, which can be taken separately or in combination, for example:
 - a) Employing specific equipment or devices designed to alleviate tissue deformations and reduce frictional forces and shear stresses such as multi-layered alternating-stiffness prophylactic dressings that cushion tissues and absorb external shear [3].
 - b) Maximizing the immersion and envelopment of the body by the supporting surface, again using special equipment or devices that mold or conform to the body contours [4].
 - c) Using innovative technologies to detect changes in markers of tissue health in order to monitor any potential onset of deformation-inflicted cell and tissue damage, ultrasound being one promising modality for detecting such changes [5].

Depending on the scenarios of intended use and target patient population, taking each of these technological directions or a combination of them should also involve testing of how the deformation absorption efficacy is affected by the environ-

ment of patients, e.g. when the environment becomes hot, moist or wet. Here we review specific examples that concern the effects of tissue deformations on the risk for pressure ulcers and the minimization of exposure to tissue deformations by means of medical devices.

Example (a) – Immersion and Envelopment of the Body by Support Surfaces

To establish the importance of immersion and envelopment in protecting tissues of frail individuals, such as those with spinal cord injuries, we have employed biomechanical computational modeling. In our published work, we have assessed support surfaces such as bed mattresses and wheelchair cushions aimed at minimizing the risk for pressure ulcers [4]. Computational modeling facilitates isolation of different risk factors associated with either the specific support surface or the individual himself [6]. Hence, the pathoanatomical variations in individuals, both between persons and over time in the same person can be determined and considered. Examples that are specific to people post spinal cord injury include muscle disuse-related atrophy, fat infiltration into muscles as a consequence of disuse, adaptation of bone shapes and contours to the disuse, and overall changes in skeletal and muscular mass with respect to fat mass [6]. Computer simulation tools are cost-effective in testing design features of support surfaces at the pre-clinical stage, and are now increasingly being adopted by the wound care industry [7].

Specifically, when there is a need to assess internal tissue loads in the weight-bearing body, the finite element method of computer simulations is extremely effective. This is a computational technique which originates from the traditional engineering disciplines for finding the internal mechanical loads (e.g. mechanical deformations, strains and stresses) in structures having complex shapes and multiple material components. In practice, the geometry of structures that are as complex as the human body is divided in the computer into numerous small elements – each with a much simpler geometry (such as small bricks or pyramids), and the equations that describe the physical and mechanical interactions (between and within tissue types) are solved by the computer for every element with respect to its neighboring elements, in order to ul-

timately construct the solution of internal load distributions to the entire organ or tissue-complex structure. The geometry of the organ or tissue structures is imported to the modeling from magnetic resonance imaging (MRI) scans, which, in the context of weight-bearing studies, may also be conducted in an open (e.g. seated) MRI configuration. Hence, the combination of MRI and computational finite element modeling provides a realistic insight into how the body, its organs, tissues and cells are deforming and overall responding biomechanically to weight-bearing loads [1].

Using MRI coupled with finite element computer modeling, as detailed above, sufficient immersion and envelopment of the body were identified as key factors in the design of a good support surface [7]. Together, immersion and envelopment represent the potential cushioning performance through minimization of internal tissue deformations, strains and stresses, particularly near the bony prominences such as the sacrum or the ischial tuberosities. Adjustability of the support surface is another key factor to achieving this end, as body types and internal anatomies vary considerably among people, and can change substantially over time, especially given the remarkable disuse-related anatomical and physiological changes during months and years of chronic sitting post a spinal cord injury [6]. Adaptability is an additional key factor, as the support surface has to be able to accommodate changes in posture and weight shifts associated with daily living throughout the entire period of intended use [4]. Furthermore, with regard to durability, a support surface should maintain its physical, mechanical and thermal properties as well as its protective efficacy over at least several years, despite exposure to degenerating conditions e.g. temperature changes, wear against materials and exposure to body fluids. An additional financial factor that is relevant and highlights the importance of adequate durability is the international trends in reimbursement policies, which are forcing an increase in the number of years of use before a replacement equipment is sponsored by public or private insurance.

Scientists and public policy-makers are in a virtual conflict regarding patient access to the equipment, consumables and services that address their needs, in particular with regard to expenditure on prevention. If scientific knowledge is insufficient with re-

gard to prevention strategies, and this may still be the case in pressure ulcer prevention research, policymakers are prone to establishing coverage and payment rules that primarily focus on financial objectives, that is, to minimize expenditure. For example, if certain support surfaces that are prescribed and reimbursed for prevention of pressure ulcers do not actually provide the intended benefits that are listed above, to the individual, the prevalence and incidence of pressure ulcers will eventually rise. Over time, this pushes the healthcare costs upwards, with regard to both the cost components imposed on the individuals and those paid by the healthcare system, insurance or government. In this regard, it should be stated that in the last decade there have been important advancements in understanding the aetiology of pressure ulcers (as reviewed in the Introduction here) and in the availability of novel research tools and methodologies to assess efficacies of support surfaces. One specific field of advancement is the use of imaging modalities combined with computational biomechanical modeling to evaluate internal tissue deformations *in vivo*, in humans, and determine how these are influenced by the interaction with a support surface [7,8]. This now facilitates objective, standardized and quantitative rating of technologies and products for hospital bed mattresses, wheelchair and bedside chair cushions, etc. Nevertheless, there are still considerable gaps between public policy and current practice in the evaluation of support surfaces, and the challenges and measures that should be applied. Here, the key factors that should be considered in any evaluation, selection and design of support surface products were reviewed, namely: immersion and envelopment, adjustability, adaptability, and durability [4,7].

Example (b) – The Case of Toilet Seating

Effective pressure ulcer prevention planning should consider all aspects of daily living, and all the potential interactions of the body with objects that contact the skin and through which forces apply, including – as a key example – episodes of using the toilet. The extent of exposure to sustained tissue deformations and mechanical stresses, as explained in the Introduction, is now known to be correlated to the risk for developing pressure ulcers and especially deep tissue injuries – the pathway for the most serious

pressure ulcers [1,2]. Tissue deformations in muscle, fat and skin are typically high (primarily in shear) on toilet seats compared to chairs. Specifically, the effective area for load transfer is smaller for toilet seats; they are often made of rigid plastic or wood (if not cushioned), and their shapes are not designed to optimize internal tissue loads and can include sharp angles, edges and other irregular geometries and structural gradients that may highly distort tissues. Again, using finite element computer modelling and this time, adding tissue oxygenation measurements during weight-bearing, we have studied deep tissue physiology and biomechanics when sitting on different toilet seats. We have quantified skin, fat and muscle tissue deformations and the patterns of change in tissue oxygenation levels over time when sitting on the commode.

As expected, tissue deformations are greater on toilets relative to chairs [9]. Moreover, the toilet-seat design characteristics strongly affect tissue loads [9]. Much like with regard to mattresses and cushions, computer modelling can effectively rate existing toilet seat designs by the potential tissue injury risk, or aid in developing new seat designs, and regardless, the toilet sitting time should be minimized [9]. In the context of minimizing the exposure to tissue deformations by maximizing immersion and envelopment (while considering functionality as well), this second example of the body-toilet interaction highlights the importance of taking a holistic approach to pressure ulcer prevention. In other words, investing in expensive pressure ulcer prevention beds, mattresses or cushions is likely to be ineffective if patients are left to sit on the toilet for long times, which exposes them to excessive tissue deformations, stresses and distortions.

Example (c) – Adjustability of Support Surfaces to Misplaced Medical Devices

We have developed multiple physical and computer model systems to investigate the conditions and scenarios at which medical device-related pressure ulcers occur. In the context of minimizing the exposure to tissue deformations, development of such experimental and computer models is essential for creating laboratory standards for testing the safety of medical devices that contact the skin of weight-bearing organs. We investigated scenarios where pieces of equipment including catheters, wires, electro-

des etc. were misplaced or forgotten under weight-bearing body parts e.g. the arms or the head [4,10]. Similarly, to the previous examples we have used computer modeling (employing the finite element method), augmented with physical phantoms (dummies equipped with force/pressure sensors) to investigate the mechanical interactions at the surface of the body (i.e. loads applied on the skin) and in deep tissues. Based on our findings, we feel that the design of medical devices and equipment used in critical care settings should be re-visited, since currently, there appears to be no attention to the safety of use with regard to the pressure ulcer risk. Much can be done with regard to design of device structures, selection of materials (e.g. matching of mechanical stiffnesses between the device and the contacting tissues: a principle called "modulus matching") and integration of mechanisms and sensors that minimize the risk of misplacement under the body. By adopting such an approach to patient safety, catheters tubes and other equipment that are used daily by people with spinal cord injuries or other frail individuals can be made safer, even if forgotten or misplaced between the patient and the support surface [10].

Discussion

In nearly two decades of research focusing at multi-scales of the pressure ulcer (injury) problem, which spans from biomechanical analyses of weight-bearing body organs, to tissues and cells, and down to the sub-cellular and molecular levels, we have demonstrated that minimization of exposure to tissue deformation is the most fundamental approach to pressure ulcer prevention [1–10]. We have quantified human tissue deformations using MRI and ultrasound to determine deformations of soft tissues such as muscle and fat in body parts and organs such as the weight-bearing buttocks, head and heels, and how they vary across healthy and non-healthy individuals, including when interventions are applied [1,3–5,7–11]. In a substantial volume of the aforementioned work we further coupled between MRI and finite element computer modeling for studies of magnitudes and distributions of tissue deformations and stresses. The effects of exposure to bodyweight loads on soft tissue viability and function, including for example the impact on transport of metabolites in cells and tissues, on perfusion and in particular the relationship between

sustained deformations and transport was highlighted in our work [1,2]. In particular, we found that exposure to sustained deformations directly affects tissue metabolism, at both the cell and tissue scales, regardless of the potential ischemic conditions [1,2]. In recent years, we have zoomed-in to the level of individual cells and cell organelles, and revealed the effects of sustained deformations and stresses on possible cytoskeletal damage and poration of the plasma membrane of deformed cells in tissues [2], which will cause loss of homeostasis over relatively short times (minutes to hours) and eventually lead to cell and tissue death. Finally and importantly, we have suggested implementation of these basic science findings in clinical practice and in product selection and development, for example how these considerations influence the selection of support surfaces for hospitalized patients and wheelchair users [4,7–11], or why would prophylactic dressings be valuable when protecting tissues from potential deformation damage in surgical or bedridden individuals [3]. Over-

all, our basic and applied research has indicated that the objective of any support surface, prophylactic dressings or other devices which contact the skin or aim at protecting tissues against pressure ulcers is to minimize the exposure to tissue deformations and stresses, both cutaneous and subcutaneous. This is as opposed to the traditional, simplistic approach of measuring interface pressures which provide partial, and sometimes misleading information with regard to the risk for pressure ulcers.

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