Finite Element Model of Lower Limb Lymphedema Under Elastic Compression

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Abstract

Introduction

In the human body, the lymphatic system plays a crucial role in maintaining fluid balance by draining and filtering lymph derived from interstitial fluid that is not reabsorbed by blood vessels. When lymphatic fluid drainage becomes impaired due to obstruction of the drainage pathways or congenital conditions (1–3), lymph accumulates, leading to tissue swelling and the development of fibrosis. This condition, known as lymphedema, particularly affects women undergoing treatments for breast and gynecological cancers (4,5).

Among the treatments available to manage lower limb lymphedema, compressive therapy using compression stockings has demonstrated satisfactory results in reducing tissue swelling and controlling leg volume (6). However, the exact impact of compression stockings on lymphatic drainage remains poorly understood.

Finite Element Analysis (FEA) has been employed to investigate upper limb lymphedema under compression (7), providing valuable insights. However, similar studies addressing lower limb lymphedema are notably absent in the current literature. To address this gap, this study proposes a FEA approach to examine the hydrostatic pressure distribution within the soft tissues of the region between the ankle and knee in a patient with lower limb lymphedema wearing a compression stocking. This investigation includes a sensitivity analysis to evaluate the effects of different soft tissues and compressive therapy on a patient-specific Finite Element (FE) model of a lymphedematous leg.

Methods

The FE model of the leg was reconstructed using segmented three-dimensional Magnetic Resonance Imaging (MRI) data from a patient with lower limb lymphedema, obtained at the University Hospital Center of Nice, France. These images enabled the differentiation of leg tissues, including fat, muscles, and bones.

Since bones are significantly stiffer than soft tissues, only fat and muscles were modeled using four-node linear tetrahedral hybrid elements with constant pressure. Additionally, the skin and fascia cruris tissues were modeled from the external surfaces of fat and muscles, respectively, using three-node triangular membrane elements.

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Neo-Hookean compressive material properties were assigned to the skin, fat, fascia cruris, and muscles. Four FE models were developed to include different combinations of tissues: one with fat and muscles; one with fat, fascia cruris, and muscles; one with skin, fat, and muscles; and one with skin, fat, fascia cruris, and muscles.

The volume of the bones was not modeled, but the nodes on their surfaces in the inner part of the leg were clamped. Symmetry boundary conditions were applied to the top and bottom surfaces of the model to constrain longitudinal displacement. Finally, the interface pressure, representing the pressure exerted by a compressive stocking on the skin surface, was calculated using Laplace's law, based on the stocking tension and the local curvature radius of the leg. FE simulations were conducted using Abaqus CAE software.

Results

The numerical simulations reveal the impact of leg morphology on the distribution of interface pressure. In areas of the skin surface where the local curvature radius is smaller, the interface pressure is significantly higher. This increase in interface pressure directly generates a higher hydrostatic pressure distribution within the soft tissues beneath these regions of the leg.

The skin and fascia cruris tissues provide resistance against the transmission of interface pressure, playing a crucial role in the hydrostatic pressure distribution within the underlying fat and muscle tissues. However, the simulations indicate that the skin exerts a greater influence than the fascia cruris in this process and contributes more significantly to the relaxation of hydrostatic pressure within the leg, effectively mitigating the pressure gradients imposed by external compression.

Discussion

The morphology of a patient's lower limb directly determines the interface pressure applied by the stocking, which, in turn, significantly impacts the hydrostatic pressure distribution within the tissues. For patients with lymphedema in the lower extremities, this morphology becomes even more complex, as the presence of edema can lead to irregular and non-uniform hydrostatic pressure patterns depending on the distribution of excess fluid within the tissues.

In the literature, existing models of compression in the lower limb do not account for either the skin or fascia cruris tissues (8). However, the findings of this study highlight the important role of the skin in regulating the mechanical response of soft tissues under compressive loading. In FE models that exclude the skin, there is a notable overestimation of hydrostatic pressure distribution in the fat and muscle tissues. Since fluid accumulation predominantly occurs within the fat tissue (9), this overestimation may result in a misunderstanding of how compressive stockings influence fluid drainage and the maintenance of limb volume. Accurately modeling the skin's contribution is, therefore, crucial for generating realistic predictions about the effectiveness of compression therapy.

Conclusions

The results emphasize the critical importance of patient-specific models in evaluating the effectiveness of compressive stockings. To further investigate these phenomena, future research will extend the current approach to a larger cohort of patients. By analysing data from multiple individuals, the study aims to capture a broader range of variations in pressure distributions arising from differences in patient-specific factors such as anatomy, tissue composition, and the severity of lymphedema. Additionally, efforts will focus on identifying correlations between simulated hydrostatic pressure distributions and observed patterns of fluid retention or fat accumulation in the affected tissues. This expanded investigation will provide a more comprehensive understanding of the mechanical and physiological responses elicited by compressive therapy, ultimately contributing to the optimization of personalized treatment strategies.

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Acknowledgements

The project was supported by the Symphonies Project funded by BPI France.