MODELING THE MECHANICAL INTERACTION OF SKIN AND ARTERIES WITH WEARABLE BLOOD PRESSURE SENSORS

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Abstract

Introduction

Hypertension (HT), the leading cause of cardiovascular morbidity, requires precise and continuous monitoring for effective management. Traditional methods relying on inflatable cuffs are limited by their intrusive nature and unsuitability for real-time tracking. Wearable devices, such as smartwatches, present a promising solution for non-invasive, continuous measurements. However, their reliability is compromised by complex technical challenges, including mechanical interactions between the sensor, subcutaneous tissues, and the underlying artery, as well as individual physiological variability. This study aims to develop a finite element method-based numerical model to analyze these interactions, providing insights that could eventually be integrated into algorithms. Here, we focus on modeling an artery located under skin layers and muscle to study pressure variations between the sensor and the skin during arterial pulsation.

Model

The model was built using COMSOL Multiphysics coupled with MATLAB for automating simulations and analyzing results. It relies on large strain analysis including hyperelastic behaviors to accurately reproduce the properties of biological tissues and the complex mechanical interactions with a pulsating artery. (1)(2)

The constitutive parameters for the material models used in this study were sourced from the literature. Tissue layers were modeled as follows: the dermis and epidermis were represented using a Neo-Hookean hyperelastic model (3). The hypodermis employed a five-parameter Mooney-Rivlin hyperelastic model (4). Muscle tissue was characterized as an Ogden-type

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hyperelastic material (5), and the tissues were stretched following the average physiological elongation of the skin at the forearm level.

The artery, situated within the muscle, was modeled using the Delfino (6) strain energy function, with an internal diameter of 1.42 mm and a wall thickness of 0.39 mm(7). Arterial blood pressure (80–120 mmHg) was simulated as a Gaussian pressure variation, representing the cardiac cycle (7).

The sensor applied pressure ranged from 0 to 140 mmHg in 1 mmHg increments, allowing the evaluation of tissue deformations and signal variations. Simulations conducted under steady-state conditions integrated large tissue deformations and arterial pressure cycles (1)(2).

Results

The hyperelastic properties of the tissue layers have a significant influence on pressure signal transmission and arterial deformations (5). Nonlinear models better captured these interactions, offering a detailed understanding of the underlying mechanisms.

By exploring the impact of these properties on tissue deformation, we found that maximum arterial deformation occurred when the transmural pressure was equal to zero, corresponding to a locally applied pressure of 65.3 mmHg. Under this condition, the detected signal variation was maximized. Beyond this threshold, the signal decreased, indicating a saturation of measurable deformations.

Continuing this analysis, the model succeeded in reproducing the signal inversion phenomenon observed clinically by PhotoPlethysmoGraphy (PPG) (9). This phenomenon, linked to interactions between the artery and surrounding tissues, was more pronounced when the artery was closer to the skin surface and when the pressure applied by the sensor was relatively low.

Conclusion

This study presents an advanced numerical model of interactions between a wearable sensor, subcutaneous tissues, and a pulsating artery. Key contributions include identifying an optimal applied pressure to maximize signal amplitude and help us to understand the signal inversion phenomena influenced by sensor location and tissue mechanical properties. These advancements will enable more accurate algorithms for continuous blood pressure monitoring, with significant implications for developing robust and reliable wearable devices.

Future steps include comparing numerical model results using physical phantoms, confirming the model's capability to reproduce experimentally observed phenomena. Additionally, factors such as interindividual variability and the impact of specific pathologies will be integrated, along with clinical validation on human subjects using ultrasound imaging to quantify tissue interactions in a patient-specific manner. This work bridges numerical modeling and clinical applications, paving the way for more effective wearable devices for cardiovascular monitoring.

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