Integrating Population-Level 4D Body Scanning and Subject-Specific Finite Element Modeling for Biomechanical Analysis of Compression Leggings on Lower Limbs

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Abstract

Compression leggings are widely used to enhance athletic performance by stabilizing soft tissue and improving circulation. A comprehensive biomechanical understanding of their effects on the lower limbs is crucial for optimized design. However, existing models often struggle to balance subject specificity with population generalizability. This study addresses this challenge by integrating population-level 4D body scanning with subject-specific finite element (FE) modeling. Using 4D body scanning and a novel anthropometric image recognition method, we quantified lower limb soft tissue deformation in 60 female participants wearing five distinct compression legging designs under both static and dynamic conditions. Principal component analysis (PCA) and K-means clustering identified three biomechanical categories based on anthropometric and body composition data. For each category, MRI-based FE models were developed for representative subjects, incorporating nine segmented muscle groups with region-specific hyperelastic properties. Simulations revealed category-dependent differences in interface pressure, tissue deformation, and muscle stress, which were validated experimentally with errors of 15.4% for pressure and 16.0% for deformation. This integrated framework enables both generalizable and precise biomechanical evaluation, offering robust guidelines for material selection and design optimization in compression leggings.

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