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Author: Li Xin

Supervisor(s): Dr. habil. Gusztáv Fekete and Dr. András Kovács

**Dissertation Title: Biomechanical Analysis of Walking Stability During
Pregnancy and the Fall-Prevention Effects of Negative Heel Shoes**

ABSTRACT BOOKLET

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1. Summary of the Context of the Research

Pregnancy is accompanied by gestational weight gain, an uneven distribution of added gestational mass, changes in connective-tissue behavior, and increased lower-limb loading. As gestation advances, additional mass accumulates mainly in the anterior trunk, while hormonal changes may alter passive tissue support. These adaptations can affect the foot, walking mechanics, and balance control. Clinically, this is important because pregnancy is associated with increased musculoskeletal discomfort and a higher risk of falls, especially in late pregnancy. However, the mechanical links among structural foot adaptation, walking strategy, and external interventions remain incompletely understood. The present dissertation addresses this problem from three related perspectives.

First, pregnancy-related changes in the foot have been described in previous studies, including increases in foot length and width, reductions in arch-related measures, and altered plantar loading. Nevertheless, the underlying mechanical drivers of these changes have not been clearly distinguished. In particular, it remains uncertain to what extent pregnancy-related foot deformation is driven by increased body weight and to what extent it is associated with reduced passive tissue support. Clarifying this issue is necessary for a more specific biomechanical interpretation of foot adaptation during pregnancy.

Second, walking during pregnancy is commonly described as slower and more conservative, with shorter stride length and wider steps. Although these changes are well documented at the level of spatiotemporal gait parameters, the underlying biomechanical mechanisms remain less clear. It is still uncertain whether this pattern should be interpreted mainly as a passive consequence of structural and loading changes or as a mechanically organized adaptation involving altered muscle-force-induced joint angular acceleration patterns across the lower limb. Model-based approaches such as pregnancy-adjusted musculoskeletal modeling and induced acceleration analysis provide a means of examining this issue.

Third, footwear is a modifiable external factor that may influence gait mechanics during pregnancy. Previous research has suggested that footwear structure can affect plantar loading, joint motion, and stability-related variables, but the biomechanical role of heel-toe drop in pregnancy remains insufficiently studied. In particular, there is limited evidence on how negative-heel footwear influences stability-related gait indicators during late pregnancy.

Against this background, the dissertation investigates pregnancy-related walking stability by linking structural adaptation of the foot, gait biomechanics in late pregnancy, and the short-term effects of footwear with different heel-toe drops. In this way, the work aims to provide a more coherent mechanical interpretation of how structural factors, walking adaptation, and footwear intervention are related during pregnancy.

2. The Aims

This dissertation examined pregnancy-related walking stability from three related perspectives: structural adaptation of the foot, walking biomechanics in late pregnancy, and the short-term biomechanical effects of footwear with different heel-toe drops.

The first aim was to examine the relative mechanical effects of gestational weight gain-related loading and reduced passive plantar ligament–fascia stiffness on foot arch deformation under simulated loading conditions. Rather than treating pregnancy-related foot change as a uniform consequence of increased external load, this part of the study aimed to distinguish the respective contributions of loading and tissue-property alteration to arch deformation patterns in a subject-specific finite element framework. Particular attention was given to changes in the transverse arch and associated redistribution of internal stress within the midfoot.

The second aim was to characterize walking adaptations during late pregnancy using spatiotemporal gait assessment, three-dimensional gait analysis, force-platform measurements, and pregnancy-adjusted musculoskeletal modeling. Induced acceleration analysis was used to examine IAA-derived muscle-force-induced joint angular acceleration patterns during stance. The purpose was to determine whether the conservative walking pattern observed in pregnancy was accompanied by altered model-estimated joint angular acceleration patterns across the lower limb.

The third aim was to determine whether footwear with different heel-toe drops could modify walking biomechanics and selected biomechanical indicators associated with stability during late pregnancy. To address this question, gait was compared under three footwear conditions: negative-heel shoes, flat shoes, and low-heel shoes. Particular attention was given to plantar loading patterns, spatiotemporal gait parameters, joint mechanics, and centre-of-mass–centre-of-pressure relationships during walking.

3. The Methods Used During the Research

To address these aims, the dissertation combined finite element modeling, experimental gait analysis, pregnancy-adjusted musculoskeletal modeling, and a controlled footwear intervention design.

For the structural analysis, a subject-specific three-dimensional finite element model of the foot was constructed from computed tomography data. The model included bones, cartilage, ligaments, plantar fascia, and surrounding soft tissues. Pregnancy-related biomechanical variation was represented by changes in body weight and passive tissue stiffness, while geometry and boundary conditions were otherwise kept constant. A full-factorial design was used to examine the main effects of body weight and tissue stiffness and their interaction. Key output variables included transverse-arch geometry, plantar pressure distribution, and von Mises stress in the midfoot region. A standardized regression-based sensitivity analysis was used descriptively to compare the direction and relative magnitude of the associations with loading, tissue stiffness, and their interaction within the simulated design space.

For the gait comparison study, walking data were collected from women in late pregnancy and non-pregnant controls. Spatiotemporal gait characteristics were obtained using a wearable gait assessment system, while three-dimensional motion capture and force-platform measurements provided synchronized kinematic and kinetic data. These data were processed using a pregnancy-adjusted OpenSim musculoskeletal model. Induced acceleration analysis was then applied to estimate muscle-force-induced joint angular acceleration patterns associated with selected lower-limb muscle groups during stance.

For the footwear intervention study, women in late pregnancy completed gait assessment under three randomized footwear conditions: negative-heel shoes, flat shoes, and low-heel shoes. The experiment followed a repeated-measures design. Spatiotemporal gait parameters, lower-limb joint kinematics, ground reaction force profiles, centre-of-pressure trajectories, and centre-of-mass–centre-of-pressure inclination angles were extracted and compared across conditions. This design allowed the short-term biomechanical effects of heel-toe drop to be examined under self-selected walking-speed conditions.

4. Scientific Results

Based on the investigations conducted in this dissertation, the following scientific results were obtained:

(1) A subject-specific finite element analysis demonstrated that pregnancy-related foot deformation is not explained by increased loading alone. Increased body weight was more strongly associated with mediolateral widening of the transverse arch, whereas reduced tissue stiffness was more strongly associated with vertical arch lowering. These findings indicate that loading and passive tissue support contribute differently to pregnancy-related foot deformation.

(2) The same finite element framework showed increased internal stress in the midfoot, with the largest numerical increase occurring in the medial cuneiform and a similarly pronounced increase occurring in the cuboid under the simulated pregnancy conditions. This result provides a subject-specific mechanical explanation for altered midfoot load transfer and possible pregnancy-related foot discomfort.

(3) Experimental gait analysis showed that women in late pregnancy walked more slowly, with shorter stride length and lower sagittal-plane joint moments than non-pregnant controls. These findings support the interpretation that late-pregnancy walking is characterized by a lower-output and more conservative walking pattern.

(4) Pregnancy-adjusted musculoskeletal modeling and induced acceleration analysis showed altered IAA-derived muscle-force-induced joint angular acceleration patterns across the hip, knee, and ankle. The clearest distal changes occurred at the ankle, where gastrocnemius-induced plantarflexion-related acceleration and tibialis-anterior-induced dorsiflexion-related acceleration were smaller in pregnant women. These model-based findings should be interpreted as biomechanical inferences rather than as direct evidence of muscle activation or neuromuscular regulation.

(5) The footwear experiment showed that negative-heel shoes reduced the peak backward COM–COP tilt angle relative to both flat and low-heel shoes, produced a short phase-specific knee-angle difference during early stance relative to low-heel shoes, and altered localized ground reaction force patterns during stance. These findings indicate that negative-heel shoes modified walking organization, lower-limb posture, force timing, and COM–COP alignment under self-selected walking-speed conditions, but they do not establish improved gait stability, greater shock absorption, or reduced fall risk.

(6) Taken together, the dissertation shows that pregnancy-related walking biomechanics are shaped by foot structural loading, conservative gait adaptation, and footwear-related mechanical constraints. These components should therefore be interpreted as mechanically related aspects of pregnancy-specific gait adaptation.

5. List of Publications Related to the Thesis

Referred articles related to this thesis:

1. Li Xin, Zhenghui Lu, Yang Song, Minjun Liang, Yi Yuan, Gusztáv Fekete, András Kovács, Dong Sun, and Yaodong Gu. "Pregnancy-induced gait alterations: meta-regression evidence of spatiotemporal adjustments." *Frontiers in bioengineering and biotechnology* 12 (2024): 1506002. Q1 IF=5.5
2. Li Xin, Zhenghui Lu, Xuanzhen Cen, Yizheng Zhou, Rongrong Xuan, Dong Sun, and Yaodong Gu. "Effect of pregnancy on female gait characteristics: A pilot study based on portable gait analyzer and induced acceleration analysis." *Frontiers in Physiology* 14 (2023): 1034132. Q1 IF=4.1
3. Li Xin, Zhenghui Lu, Dong Sun, Rongrong Xuan, Zhiyi Zheng, and Yaodong Gu. "The influence of a shoe's heel-toe drop on gait parameters during the third trimester of pregnancy." *Bioengineering* 9, no. 6 (2022): 241. Q3 IF=4.1
4. Lu Zhenghui, Xin Li, Dong Sun, Yang Song, Gusztáv Fekete, András Kovács, Zixiang Gao, Jianjun Zheng, Liangliang Xiang, and Yaodong Gu. "Computationally tuned dual-layer lattice pads adapted to gait-induced pressure distribution." *npj Advanced Manufacturing* 2, no. 1 (2025): 43.
5. Jiang, Xiaojie, Xin Li, Yining Xu, Dong Sun, Julien Baker, and Yaodong Gu. "Can PAPE-induced increases in jump height be explained by jumping kinematics?." *Molecular & Cellular Biomechanics* 20, no. 2 (2023): 67. Q4 IF=1.0
6. Lu Zhenghui, Xin Li, Dong Sun, Yang Song, Gusztáv Fekete, András Kovács, Kámán András, and Yaodong Gu. "Parametric cushioning lattice insole based on finite element method and machine learning: A preliminary computational analysis." *Journal of Biomechanics* 184 (2025): 112674. Q1 IF=2.7
7. Lu Zhenghui, Xin Li, Dong Sun, Yang Song, Gusztáv Fekete, András Kovács, and Yaodong Gu. "Will this be the next step? A systematic review of 3D printing in footwear biomechanics." *Footwear Science* 17, no. 2 (2025): 127-142. Q2 IF=3.8
8. Lu Zhenghui, Xin Li, Ming Rong, Julien S. Baker, and Yaodong Gu. "Effect of rearfoot valgus on biomechanics during barbell squatting: A study based on OpenSim musculoskeletal modeling." *Frontiers in neurorobotics* 16 (2022): 832005. Q2 IF=3.2
9. Lu Zhenghui, Xin Li, Rongrong Xuan, Yang Song, István Bíró, Minjun Liang, and Yaodong Gu. "Effect of heel lift insoles on lower extremity muscle activation and joint work during barbell squats." *Bioengineering* 9, no. 7 (2022): 301. Q3 IF=4.1
10. Shen, Linxiao, Dong Sun, Yufei Fang, Zhenghui Lu, Xin Li, Yufan Xu, Yang Song, Chengyuan Zhu, Xuanzhen Cen, Gusztáv Fekete, Monèm Jemni, and Yaodong Gu. "Foot Progression Angle Modulates Three-Dimensional Lower-Limb Biomechanics in Flexible Flatfoot: Kinematic–Kinetic Patterns and Clinical Implications." *Journal of Foot and Ankle Research* 19, no. 1 (2026): e70126. Q2 IF=2.2
11. Chen, Jie, Xin Li, Patria A. Hume, Hannah Wyatt, and Julie Choisine. "Multi-segment models for kinetic analysis of women during pregnancy: A systematic review." *Gait & Posture* (2025). Q3 IF=2.2
12. Li, Xin, Ntwali Adrien, Julien S. Baker, Qichang Mei, and Yaodong Gu. "Novice female exercisers exhibited different biomechanical loading profiles during full-squat and half-squat practice." [*J. Biology*, 2021, 10(11): 1184. Q2 IF=3.5