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**Dissertation Title: Developmental Gait Biomechanics and Task-Specific Plantar Loading in Children: Implications for Sensory Processing Disorder and Balance**

**ABSTRACT BOOKLET**

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## 1. Summary of the Context of the Research

Human gait represents a highly integrated neuromechanical system that matures progressively throughout childhood, accompanied by synchronized development of the musculoskeletal system, motor control mechanisms, and sensory feedback pathways. Gait symmetry has long been regarded as a key indicator of mature and efficient locomotion, yet real-world movements such as running and directional turning inherently involve unequal limb roles and naturally introduce task-dependent asymmetry. Despite extensive studies on pediatric gait development, conventional assessments rely heavily on straight-line walking at low demand, which often fails to capture latent asymmetries or functional adaptations under dynamic conditions. Furthermore, sensory processing disorder (SPD) is closely associated with sensorimotor integration deficits and impaired balance control, but valid and sensitive biomechanical markers for characterizing task-specific locomotor abnormalities in SPD children remain limited. Meanwhile, typical developmental asymmetry, limb dominance effects, and task-induced adaptations are rarely examined within a unified analytical framework, leading to insufficient evidence for clinical assessment and targeted intervention.

This dissertation is situated within the interdisciplinary context of developmental biomechanics, pediatric motor control, and clinical rehabilitation. It addresses several critical research gaps: the lack of a task-sensitive evaluation framework for gait asymmetry covering walking, running, and 90° turning; incomplete understanding of how limb dominance modulates plantar loading and inter-limb coordination; unclear biomechanical profiles of SPD children under dynamic challenges; insufficient evidence of joint-level kinematic and kinetic asymmetry in adolescents; and the need for a high-resolution time-series analytical approach to detect phase-specific differences. The research is further motivated by strong clinical and practical demands, including early identification of developmental abnormalities, objective evaluation of balance and motor control in children with sensory dysfunction, and scientific guidance for youth locomotor health and injury risk reduction. Against this background, the dissertation establishes a comprehensive research paradigm integrating plantar pressure measurement, three-dimensional motion capture, force plate testing, and one-dimensional statistical parametric mapping (SPM1d). Three cohorts including typically developing children, children with SPD, and healthy adolescents were tested under standardized barefoot conditions across four representative tasks: straight walking, straight running, 90° turning while walking, and 90° turning while running. Outcome measures included center of pressure (COP) trajectory, Foot Balance Index (FBI), regional plantar loading, ground reaction forces, and lower-limb kinematics and kinetics.

By systematically quantifying developmental patterns, task-dependent modulations, and clinical group differences, this research contextualizes gait asymmetry as a normal and functionally meaningful feature of development rather than a pathological deviation. It also provides a translational evidence base for task-based assessment in clinical settings and promotes the understanding of developmental gait control from a task-dependent and sensorimotor-integrated perspective.

## 2. The Aims

In response to the foregoing research context and unresolved challenges in pediatric developmental gait biomechanics, task-dependent plantar loading characteristics, and clinical evaluation deficits related to sensory processing disorder, this dissertation aims to establish a comprehensive, task-sensitive analytical paradigm for quantifying developmental gait asymmetry and balance control across typical development and clinical populations. The central objective is to systematically reveal how task demands, limb dominance, and sensory processing capacity shape plantar loading patterns, center-of-pressure control, and lower-limb biomechanical strategies, and to provide an evidence-based translational framework for clinical assessment, motor function evaluation, and youth performance monitoring. The specific research objectives are as follows:

First, to establish a standardized task-dependent evaluation framework for pediatric gait asymmetry covering walking, running, and 90° turning. By integrating plantar pressure measurement, center of pressure (COP) trajectory analysis, and Foot Balance Index (FBI) calculation, this study aims to quantify phase-specific characteristics of bilateral asymmetry during the full stance phase. One-dimensional statistical parametric mapping (SPM1d) will be used to identify stance intervals with significant inter-limb differences, so as to clarify how low- and high-demand tasks modulate gait symmetry and reveal normative developmental patterns of task-dependent asymmetry.

Second, to clarify the quantitative relationship between limb dominance and gait asymmetry in typically developing children and adolescents. This study aims to identify consistent side-related biomechanical signatures in plantar loading distribution, COP progression, and foot posture bias among right-leg-dominant individuals. It will further determine the functional contributions of dominant and non-dominant limbs to support, stability, and propulsion during steady and directional locomotion, and verify whether developmental asymmetry is functionally organized rather than a random deficit.

Third, to identify distinct plantar loading and balance control strategies in children with sensory processing disorder (SPD) under graded task demands. This study aims to compare SPD children with typically developing controls during walking, running, and turning, to reveal whether group differences are masked during low-demand gait but amplified under dynamic challenges. It will quantify midfoot dominance, reduced forefoot push-off, restricted pronation, and limited medial-lateral weight transfer as objective biomechanical markers for evaluating balance and sensorimotor control in SPD.

Fourth, to systematically reveal joint-level kinematic and kinetic asymmetry profiles in healthy adolescents during linear and turning gaits. This study aims to quantify bilateral differences in ankle, knee, and hip angles, velocities, joint moments, powers, and joint reaction forces using three-dimensional motion capture and force plate measurement. It will clarify how turning maneuvers magnify inter-limb asymmetry and support the understanding that functional asymmetry is normal and task-enhanced in youth populations.

Fifth, to validate and promote a high-resolution time-series analytical paradigm for pediatric gait assessment. By normalizing full stance-phase data and applying SPM1d, this study aims to capture phase-specific significant differences that discrete peak indicators cannot detect, thereby improving the sensitivity, interpretability, and clinical applicability of gait asymmetry assessment for children and clinical populations.

Sixth, to establish an integrated translational framework for developmental gait assessment that

combines plantar pressure measurement, 3D motion capture, force plate testing, SPM1d statistical analysis, and clinical interpretation. Through multi-cohort verification, this framework will be used to distinguish typical development, task-induced adaptive changes, and SPD-related biomechanical alterations, and to support clinical screening, rehabilitation evaluation, and youth locomotor development and injury risk monitoring.

Through the systematic completion of these objectives, this dissertation seeks to advance fundamental understanding of developmental gait biomechanics and provide a unified, task-based methodological platform for pediatric clinical assessment and sensorimotor function evaluation.

### 3. The Methods Used During the Research

To achieve the defined research objectives, this study established a standardized, multi-modal biomechanical framework for investigating developmental gait asymmetry, task-specific plantar loading, and balance control in children and adolescents. The overall methodology followed a rigorous cross-sectional workflow integrating participant recruitment, ethical approval, standardized barefoot testing, multi-device data acquisition, time-series data processing, and one-dimensional statistical analysis, ensuring high reliability, reproducibility, and clinical interpretability across all experimental conditions.

At the participant selection stage, three age- and gender-matched cohorts were enrolled under ethical approval and written informed consent from guardians. Group A included 15 typically developing healthy female children. Group B consisted of 12 male children, subdivided into 6 children with sensory processing disorder (SPD) and 6 typically developing age-matched controls. Group C comprised 15 healthy male adolescents. All participants were right-leg dominant confirmed by a ball-kicking test, and none had a history of lower-limb injury, surgery, or orthopedic disorders within six months prior to testing. All tests were performed under barefoot conditions to eliminate the confounding effects of footwear.

At the experimental protocol stage, all participants completed four standardized locomotor tasks along a 20-meter walkway: straight walking, straight running, 90° turning while walking, and 90° turning while running. For turning trials, only the inside foot (stance limb) was analysed according to turn direction. Adequate practice trials were provided to familiarize participants with the tasks, and multiple valid trials were collected for each condition to ensure data stability and reproducibility. At the data acquisition stage, multi-modal synchronous measurement systems were used. Plantar pressure and center of pressure (COP) trajectories were collected using a 2.0 m × 0.4 m RsScan FootScan pressure platform with 16,384 sensors at 480 Hz, covering 10 anatomical foot regions. For Group C, three-dimensional lower-limb kinematics were recorded using an 8-camera Vicon motion capture system at 200 Hz, synchronized with a Kistler force platform collecting ground reaction forces (GRF) at 1000 Hz. Outcome variables included COP trajectory, Foot Balance Index (FBI), regional plantar loading, vertical GRF, joint angles, angular velocities, joint moments, mechanical powers, and joint reaction forces.

At the data processing and normalization stage, all stance-phase data were segmented from initial contact to toe-off and time-normalized to 0–100% of the stance cycle using cubic spline interpolation. COP trajectories were processed to evaluate medial–lateral weight transfer and foot pronation–supination patterns. The Foot Balance Index (FBI) was calculated to quantify forefoot–heel loading bias. Kinematic and kinetic data were filtered using fourth-order zero-phase Butterworth filters and further processed in MATLAB and OpenSim using inverse dynamics to derive joint-level variables. All data processing was conducted using FootScan software and custom MATLAB scripts.

At the statistical analysis stage, normality was first examined using the Shapiro-Wilk test. One-dimensional Statistical Parametric Mapping (SPM1d) was then applied to perform two-sample t-tests along the entire stance phase at a significance level of  $\alpha = 0.05$ . This method enabled continuous detection of phase-specific significant differences between limbs, tasks, or groups, which cannot be fully identified using traditional discrete peak indicators. The analytical framework supported high-resolution comparisons of asymmetry magnitude, timing, and distribution across all

conditions.

Through this complete and standardized methodological pipeline, the study reliably quantified task-dependent gait asymmetry, limb dominance effects, and unique plantar loading patterns in children with SPD. The established workflow provides a sensitive, repeatable, and clinically meaningful approach for evaluating developmental gait biomechanics and sensorimotor control in pediatric populations.

## 4. Scientific Results

Based on the systematic investigations conducted in this dissertation, the following innovative scientific contributions have been achieved:

(1) A task-dependent pediatric gait asymmetry evaluation framework covering walking, running, and 90° turning was established. Using one-dimensional statistical parametric mapping (SPM1d), the phase-specific characteristics of center of pressure (COP) trajectory, foot balance index (FBI), and plantar loading asymmetry were quantitatively identified. This framework reveals that asymmetry is minimal during low-demand walking but significantly amplified under running and turning, providing a normative biomechanical basis for assessing typical developmental gait.

(2) A quantitative mapping between limb dominance and gait asymmetry in children and adolescents was clarified. In right-leg-dominant participants, the right foot tends toward pronation with medial loading bias, while the left foot exhibits supination and lateral loading characteristics. The dominant limb contributes more to propulsion and displays greater joint moments and power, confirming that developmental asymmetry is functionally organized rather than random deficit.

(3) A distinct plantar loading strategy in children with sensory processing disorder (SPD) was identified. Under low-demand walking, SPD children show comparable gross gait patterns to typically developing children; under high-demand running and turning, they rely on a midfoot-dominant loading pattern with reduced forefoot push-off, restricted foot pronation, and limited medial–lateral weight transfer. These findings provide objective biomechanical markers for evaluating balance and motor control in SPD.

(4) A joint-level kinetic and kinematic asymmetry profile in healthy adolescents was systematically revealed. Healthy adolescents exhibit extensive bilateral differences in ankle, knee, and hip angles, velocities, moments, powers, and joint reaction forces. Asymmetry is widespread during linear gait and further magnified during turning, supporting the view that functional asymmetry is normal in youth populations and task-dependently enhanced.

(5) A high-resolution time-series analytical paradigm for pediatric gait was validated. By normalizing full stance phase data and applying SPM1d, phase-specific significant intervals were detected that discrete peak indicators cannot capture. This method improves the sensitivity and interpretability of gait asymmetry assessment, especially for children and clinical populations.

(6) An integrated translational framework for developmental gait assessment was established, integrating plantar pressure measurement, three-dimensional motion capture, force plate testing, SPM1d statistical analysis, and clinical interpretation. Multi-cohort experiments verified its reliability in distinguishing typical development, task-induced adaptation, and SPD-related alterations, supporting clinical screening, rehabilitation evaluation, and youth locomotor development and injury risk monitoring.

## 5. List of Publications Related to the Thesis

### Referred articles related to this thesis:

1. **Wei Liu**, Nan Li, Yuming Wang and Gusztav Fekete\*. Lower Limb Asymmetry in Adolescent Gait: A Cross-Sectional Study of Walking, Running, and Turning with Insights for Promoting Lifelong Physical Activity. *Physical Activity and Health*, 2026, Q3
2. **Wei Liu**, Liu Xu, Haidan Wu, Yile Wang, Hanhui Jiang, Zixiang Gao, Endre Jánosi, Gusztav Fekete\*, Qichang Mei and Yaodong Gu,\*. Bilateral Asymmetries of Plantar Pressure and Foot Balance During Walking, Running, and Turning Gait in Typically Developing Children. *Bioengineering*, 2025, Q3, IF=3.8
3. **Wei Liu**, Mei, QC, Yu, PM, Gao, ZX, Hu, QL, Fekete, G, Istvan, B, & Gu, Y. Biomechanical Characteristics of the Typically Developing Toddler Foot: A Narrative Review. *Children-Basel*, 2022, Q2, IF=2.835
4. Caiting Zhang, Yang Song\*, Qiaolin Zhang, Ee-Chon Teo and **Wei Liu**.\*. Biomechanical Study of Symmetric Bending and Lifting Behavior in Weightlifter with Lumbar L4-L5 Disc Herniation and Physiological Straightening Using Finite Element Simulation. *Bioengineering*, 2024, Q3, IF=3.8
5. Chengyuan Zhu, Yang Song, Yufan Xu, Aojie Zhu, Julien S. Baker, **Wei Liu**.\* and Yaodong Gu\*. Toe box shape of running shoes affects in-shoe foot displacement and deformation a randomized crossover study. *Bioengineering*, 2024, Q3, IF=3.8
6. Enze Shao., Qichang Mei., Julien S. Baker., István Bíró., **Wei Liu**.\*, and Yaodong Gu\*. The effects of non-Newtonian fluid material midsole footwear on tibial shock acceleration and attenuation-Correspondence. *Frontiers in Bioengineering and Biotechnology*, 2023, Q1, IF=6.064
7. Enze Shao., Qichang Mei., Tongjun Ye., Bálint Kovács., Julien S. Baker., **Wei Liu**.\*, Yaodong Gu\*. The Effects of 5 km Interval Running on the Anterior Cruciate Ligament Strain and Biomechanical Characteristic of the Knee Joint: Simulation and Principal Component Analysis. *Applied Sciences*, 2023, Q2, IF=2.838
8. Yuan Wang., Hanhui Jiang., Lin Yu1.,\* Zixiang Gao., **Wei Liu**., Qichang Mei.,\* and Yaodong Gu. Understanding the Role of Children Footwear on Children Feet and Gait Development: A Systematic Scoping Review. *Healthcare*, 2023, Q2, IF=2.4
9. Yu, L., Yu, PM., **Wei Liu**., Gao, ZX., Sun, D., Mei, QC., Fernandez, J., & Gu, Y. Understanding Foot Loading and Balance Behavior of Children with Motor Sensory Processing Disorder. *Children-Basel*, 2022, Q2, IF=2.835
10. Yu, L., Mei, QC., Xiang, LL., **Wei Liu**., Mohamad, NI., Istvan, B., Fernandez, J., & Gu, Y. Pricipal Component Analysis of the Running Ground Reaction Forces with Different Speeds. *Frontiers in Bioengineering and Biotechnology*, 2021, Q1, IF=6.064

### International conference abstracts related to this thesis:

1. The 7th International Conference on Material Strength and Applied Mechanics (MSAM 2024). Title: Biomechanical Analysis of Gymnastics Movements Using Wearable Motion Capture Systems and Linear Sensors: A Case Study of the Kipping Bar Muscle-Up. 2024. Hungary (Oral presentation).