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

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Content

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

Abstract

Human gait develops through childhood as motor control, musculoskeletal capacity, and sensory feedback mature together. Although gait symmetry is often treated as a marker of mature and efficient locomotion, many daily and sport-related movements require unequal limb roles, particularly during faster speeds and changes of direction. Sensory processing disorder (SPD) is linked with sensory–motor integration difficulties and reduced balance control, yet biomechanical markers that capture task-dependent deficits remain limited. This thesis quantified how task demands (straight walking, straight running, 90° turning while walking, and 90° turning while running) alter plantar loading and inter-limb symmetry across development, and evaluated whether children with SPD show distinct plantar loading and COP control strategies during dynamically challenging tasks.

Three cohorts were assessed under standardised barefoot conditions on a 20 m walkway. Group A comprised 15 healthy female children (age 7.0 ± 1.3 years). Group B comprised 12 male children, including an SPD subgroup ($n = 6$; age 5.83 ± 1.17 years) and a typically developing control subgroup ($n = 6$; age 7.1 ± 1.2 years). Group C comprised 15 healthy male adolescents (age 15.4 ± 1.05 years), all identified as right-leg dominant using a ball-kicking preference test. Plantar pressure data were collected using an RsScan FootScan pressure plate (2.0 m × 0.4 m; 16,384 sensors; 480 Hz) and summarised as time-normalised regional force curves across 10 anatomical foot regions, together with COP trajectories and a Foot Balance Index (FBI) derived from regional peak pressures. For Group C, three-dimensional kinematics (8-camera Vicon, 200 Hz) and ground reaction forces (Kistler force platform, 1000 Hz) were recorded to characterise joint angles, moments, powers, and joint reaction forces. Time-series were normalised to 0–100% stance and analysed using one-dimensional statistical parametric mapping (SPM1d; $\alpha = 0.05$) to identify stance-phase intervals with significant left–right or group differences.

Across cohorts, measurable asymmetry was present in healthy participants, but its magnitude and timing depended strongly on task demand. In Group A, COP trajectories differed between left and right feet across the full stance phase during both walking and running ($p < 0.001$), indicating consistent side-related patterns in medio-lateral weight transfer even in typical development.

Turning produced direction-dependent COP deviations consistent with inside-foot pivot demands, and left-turn versus right-turn stances differed significantly over substantial portions of stance ($p < 0.001$). Plantar pressure asymmetry in straight walking was limited, with a notable side difference at the second metatarsal region near late stance (approximately 76%–95% of the contact phase, $p < 0.01$). In contrast, higher-demand tasks amplified regional differences; for example, during turning while walking, the second metatarsal region differed between turn directions during late stance (~76%–92%, $p < 0.01$), and during turning while running, lateral forefoot loading showed broad stance-phase differences (e.g., fifth metatarsal ~39%–88%, $p < 0.01$).

The SPD cohort showed a task-specific profile in which between-group differences were minimal in low-demand gait but emerged under higher dynamic demand. In level walking, no statistically significant SPD–control differences were detected in regional plantar pressure distributions. During running, controls generated greater vertical ground reaction force in the left foot during mid stance (approximately 22%–63% of stance, $p < 0.001$) and expressed greater distal loading consistent with a stronger push-off pattern, whereas SPD children demonstrated a midfoot-dominant strategy. Specifically, the SPD group showed greater midfoot loading in the left foot during mid stance (29%–57%, $p < 0.001$) and in the right foot for almost the entire stance (approximately 6%–100%, $p < 0.001$). COP analysis further indicated reduced medial shift in SPD during late stance of the right foot in straight running (~90%–100%, $p < 0.05$), and turning highlighted additional differences: during left turns, the right (inside) foot COP path differed between groups from approximately 16%–69% of stance ($p < 0.001$). FBI findings were consistent with restricted stance-phase modulation in SPD, with a significant right-foot difference during running (~47%–63% of stance, $p < 0.001$).

In adolescent athletes, joint-level biomechanics demonstrated that inter-limb differences can be extensive even in healthy, trained populations, and that turning increases both the duration and complexity of asymmetry. During straight running, the right ankle angle differed from the left for 0%–71% and 85%–100% of stance ($p < 0.001$ in early stance; $p < 0.026$ in late stance), the right knee angle differed during early stance (0%–24%, $p < 0.017$), and the hip angle differed across the full stance phase (0%–100%, $p < 0.001$). Joint reaction forces were also asymmetric, with right hip joint force higher for 0%–72% and 75%–100% of stance ($p < 0.01$). During turning while running, asymmetry expanded to near-whole-stance differences in ankle angle (approximately 18%–100%, $p < 0.001$) and broad differences in joint moments and power, consistent with unequal braking and propulsion roles between inside and outside limbs.

Overall, this thesis demonstrates that minor gait asymmetry is a normal characteristic of development, but that running and 90° turning substantially magnify asymmetry in plantar loading, COP control, and joint mechanics. Low-demand walking may underestimate meaningful differences in balance-related control, particularly in SPD. Dynamic task protocols combined with time-series

SPM provide a practical framework for identifying task-specific adaptations, supporting clinical assessment and intervention design for sensory–motor dysfunction, and informing performance and injury-risk considerations in youth who routinely perform high-demand maneuvers.

Abbreviations

ACL：Anterior Cruciate Ligament

C3D：Coordinate 3D file format

COM：Center of Mass

COP：Center of Pressure

DCD：Developmental Coordination Disorder

FBI：Foot Balance Index

GRF：Ground Reaction Force

MATLAB：MATLAB computing environment

SEM：Standard Error of the Mean

SPM：Statistical Parametric Mapping

SPM1D：One-dimensional Statistical Parametric Mapping

SPD：Sensory Processing Disorder

SUM：Sum of plantar pressure

WHO：World Health Organization

LH：Lateral Heel

MH：Medial Heel

MF：Midfoot

M1–M5：Metatarsal 1–5

MH1–MH5：Metatarsal head/region 1–5

T2：Toe 2

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1. Introduction

Human locomotion in childhood is not a simple scaled-down version of adult gait, but a developing neuromechanical behavior shaped by growth, sensory integration, postural control, and task demands. As children mature, the locomotor system must continuously solve the competing requirements of forward progression, stability, and adaptability while the foot, the lower-limb joints, and the underlying control systems are all changing. For this reason, pediatric gait should be interpreted not only in terms of whether movement is efficient or symmetric under simple laboratory conditions, but also in terms of how locomotor strategies are reorganized when the task becomes more demanding, when limb roles diverge, and when sensory–motor processing is challenged.

Within this broader context, several themes converge as the foundation of this thesis. First, plantar loading and center of pressure behavior provide a functional window into how the developing foot interacts with the ground and how balance is regulated during stance. Second, gait symmetry must be treated as a context-dependent rather than absolute characteristic, because asymmetry may reflect normal developmental variability, limb dominance, and task-specific coordination rather than pathology alone. Third, locomotor tasks such as running and turning are especially informative because they increase mechanical and control demands and may reveal differences that remain hidden during straight-line walking. Finally, the inclusion of children with sensory processing difficulties extends the developmental question into a clinically meaningful domain by examining whether altered sensory integration is associated with distinct loading strategies and balance-related adaptations under dynamic conditions.

Accordingly, this study is guided by the view that gait asymmetry should be interpreted at multiple levels: as a developmental phenomenon, as a task-dependent biomechanical response, and as a potentially clinically relevant marker when sensory–motor control is compromised. By integrating plantar pressure, center of pressure, and joint-level biomechanical evidence across healthy children, children with sensory processing difficulties, and healthy adolescents, this study seeks to clarify when asymmetry is expected, when it is amplified, and why its interpretation must remain linked to developmental stage, locomotor task, and functional context. On this basis, the present chapter first outlines gait as an integrated neuromechanical system, then develops the relevant background on foot maturation, symmetry and limb dominance, turning mechanics, sensory contributions to locomotion, and the translational relevance of plantar loading in pediatric movement research.

1.1 Human Gait as an Integrated Neuromechanical System

Human gait is commonly described as a cyclical locomotor pattern in which the body translates forward through a coordinated series of segmental motions, especially involving the hip, knee, ankle, and foot. At the most fundamental level, gait provides a mechanical solution to the competing requirements of forward progression, support against gravity, and maintenance of stability during single-limb support. Classic gait descriptions emphasize that the gait cycle is composed of alternating phases in which each limb transitions from stance (providing support and propulsion) to swing (advancing to the next step), and that many clinically meaningful metrics can be derived from this repeating structure, including spatiotemporal variables, joint kinematics, and kinetic signatures such as ground reaction forces and joint moments [1].

However, gait is not merely a mechanical pattern generator. It is a multi-system behavior produced by tightly coupled interactions among the nervous system, musculoskeletal system, and sensory feedback pathways. In children, gait is particularly informative because it provides an externally observable "readout" of underlying developmental processes. The emergence and refinement of walking reflect not only the growth of bones and soft tissue but also the maturation of central and peripheral neural control, sensorimotor integration, and the formation of robust strategies for balance and adaptation. As such, gait analysis has become a cornerstone method for both basic biomechanical research and clinical evaluation of neuromotor development.

From a biomechanical perspective, gait can be viewed as the dynamic management of the body's center of mass (COM) over a moving base of support. Even in "simple" straight-line walking, the body continuously regulates COM excursions and performs step-to-step transitions while maintaining a stable margin of safety. In early development, these demands are heightened because the child's body dimensions, segment inertias, and strength capacities are changing quickly; thus, the control problem itself is non-stationary. Children are not simply miniature adults with scaled dimensions. Instead, they are developing organisms in which morphology, neuromuscular control, and skill acquisition co-evolve over time.

Because of this, one of the major aims of pediatric gait biomechanics is to describe how typical gait patterns emerge, how they change with age and experience, and what constitutes the boundary between typical variability and clinically meaningful deviation. Establishing this boundary is essential for two reasons. First, it enables earlier recognition of motor impairment or atypical development. Second, it provides the mechanistic foundation for designing interventions to guide development toward healthier, more efficient locomotor behaviors

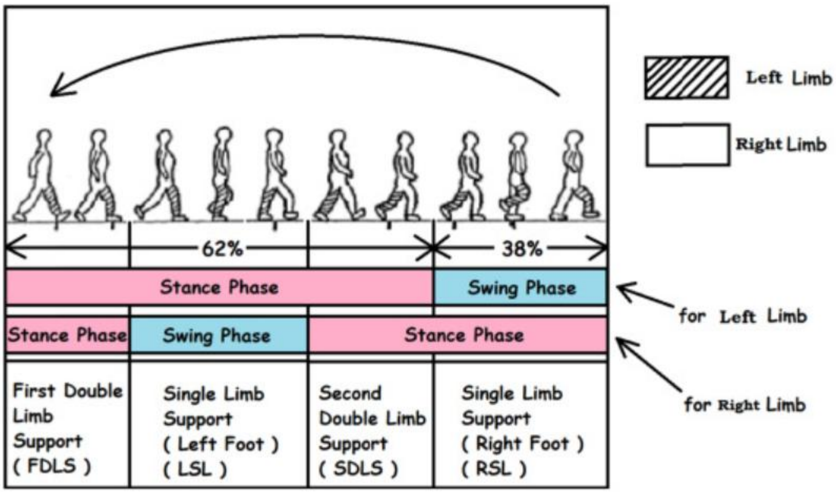


Figure 1.1.1 Division of a gait cycle considering both limbs [1].

1.2 Developmental Milestones and the Emergence of Independent Walking

Independent walking is among the most important developmental milestones in early childhood. It transforms how children interact with their environment, expands opportunities for exploration, and accelerates cognitive and social development through increased autonomy. Yet the onset of independent walking is not a single “event” but a process: infants transition through supported stepping, assisted cruising, and early independent steps before settling into more stable and consistent patterns. The timing of these milestones varies substantially among typically developing children. Large-scale motor development studies indicate that while many children begin to walk independently around the end of the first year, a meaningful proportion begins later without necessarily indicating pathology [2]. This variability underscores a key challenge: clinicians and researchers must distinguish normal developmental diversity from early signs of neuromotor impairment.

In parallel with this milestone, rapid developmental changes occur across multiple systems relevant to gait. Early childhood is characterized by marked changes in skeletal structure and ossification patterns (including within the foot), the emergence and reshaping of the medial longitudinal arch, growth of muscles and connective tissues, and the progressive maturation of postural control systems. These changes alter the mechanical constraints and capabilities of the locomotor system, and they shape the strategies that young walkers use to achieve stable movement.

One of the best-supported ideas in developmental locomotion is that gait patterns are not “preprogrammed” to appear fully formed; instead, stable walking emerges through repeated practice, exploration, and the gradual refinement of control strategies. Children learn to manage their body dynamics in an upright posture under changing constraints—both internal (growth, strength, neural maturation) and external (surface, footwear, environment). Consequently, early gait patterns reflect an interplay between immature neuromuscular control and the functional goal of remaining upright while moving forward.

A related point is that children adjust locomotion to changing body dimensions. As growth proceeds, the same control strategy may no longer generate the same outcome because segment lengths, mass distribution, and moment arms change. Children therefore must continuously recalibrate movement. This is consistent with evidence that infants adapt locomotor behavior to changing body dimensions and constraints during development [3]. From a biomechanics viewpoint, this is profound: walking development is simultaneously a story of morphological growth and control learning, and these dimensions cannot be separated.

1.3 Biomechanical Features of Early Childhood Gait

Early independent walking is often described as “immature” because it differs systematically from adult gait. Several characteristic features are consistently reported in novice walkers: (i) A wide base of support (increased step width), which likely increases the lateral stability margin and reduces the likelihood of sideways loss of balance. (ii) High cadence and short steps, reflecting a strategy in which frequent foot placement is used to manage stability and compensate for limited single-limb support control. (iii) Prolonged double support, meaning that toddlers spend a greater proportion of the gait cycle with both feet in contact with the ground, likely as a conservative stabilization strategy. (iv) Increased variability across steps, which reflects ongoing exploration and incomplete refinement of motor patterns. (v) Distinct foot contact patterns, often including flat-foot contact or unstable heel strikes during the earliest stages, before evolving toward more consistent heel-to-toe rollover.

These features can be interpreted as a stability-first solution in a system with limited neuromuscular capacity. They are not necessarily “deficits”; rather, they are adaptive responses to the demands of upright locomotion under immaturity constraints.

1.3.1 Development of Spatiotemporal Control in Early Walking

Across the first months and years after walking onset, spatiotemporal parameters evolve in ways that suggest improving balance control and coordination. As toddlers gain experience, step width tends to narrow, cadence gradually becomes less extreme, walking speed increases, and the proportion of time spent in double support decreases. Importantly, these changes are not purely linear with chronological age; they also depend on walking experience, which is not the same as age because children begin walking at different times and accumulate practice at different rates.

A central developmental theme is the shifting balance between stability and economy. Early walking is comparatively costly and variable. Over time, children learn strategies that reduce unnecessary movement, optimize step-to-step transitions, and improve energy exchange mechanisms. This shift is also linked to the development of postural control. The ability to regulate body orientation and to manage COM excursions improves with maturation of balance systems and with practice of upright locomotion. Research on the development of postural control during the first years of walking supports the view that the control of gravity-related forces becomes more refined as children progress through early childhood [4]. As this refinement occurs, the locomotor system can “afford” narrower step widths and shorter double-support periods, enabling faster and more efficient movement.

1.3.2 Kinematic and Kinetic Coordination During Gait Maturation

Beyond spatiotemporal metrics, the maturation of gait is reflected in the time courses of joint angles and joint moments. Early walkers often demonstrate limited and less consistent joint excursions, as well as less adult-like coordination patterns. From a kinetics perspective, toddlers also show evolving patterns of ground reaction forces and load distribution. The transition from flatter foot contact toward more consistent heel contact is a particularly important feature because it indicates changes in foot function, ankle control, and the development of rollover mechanics.

The foot plays a central role in these developments. It is both a contact interface with the ground and a complex mechanical structure with multiple bones, joints, and soft tissue elements that must absorb impact, maintain stability, and contribute to propulsion. The foot's functional maturation therefore influences the whole-limb and whole-body gait strategy. This motivates a more focused discussion of the developing foot and plantar loading—which becomes especially important when considering symmetry and asymmetry in gait (Figure 1.3.1).

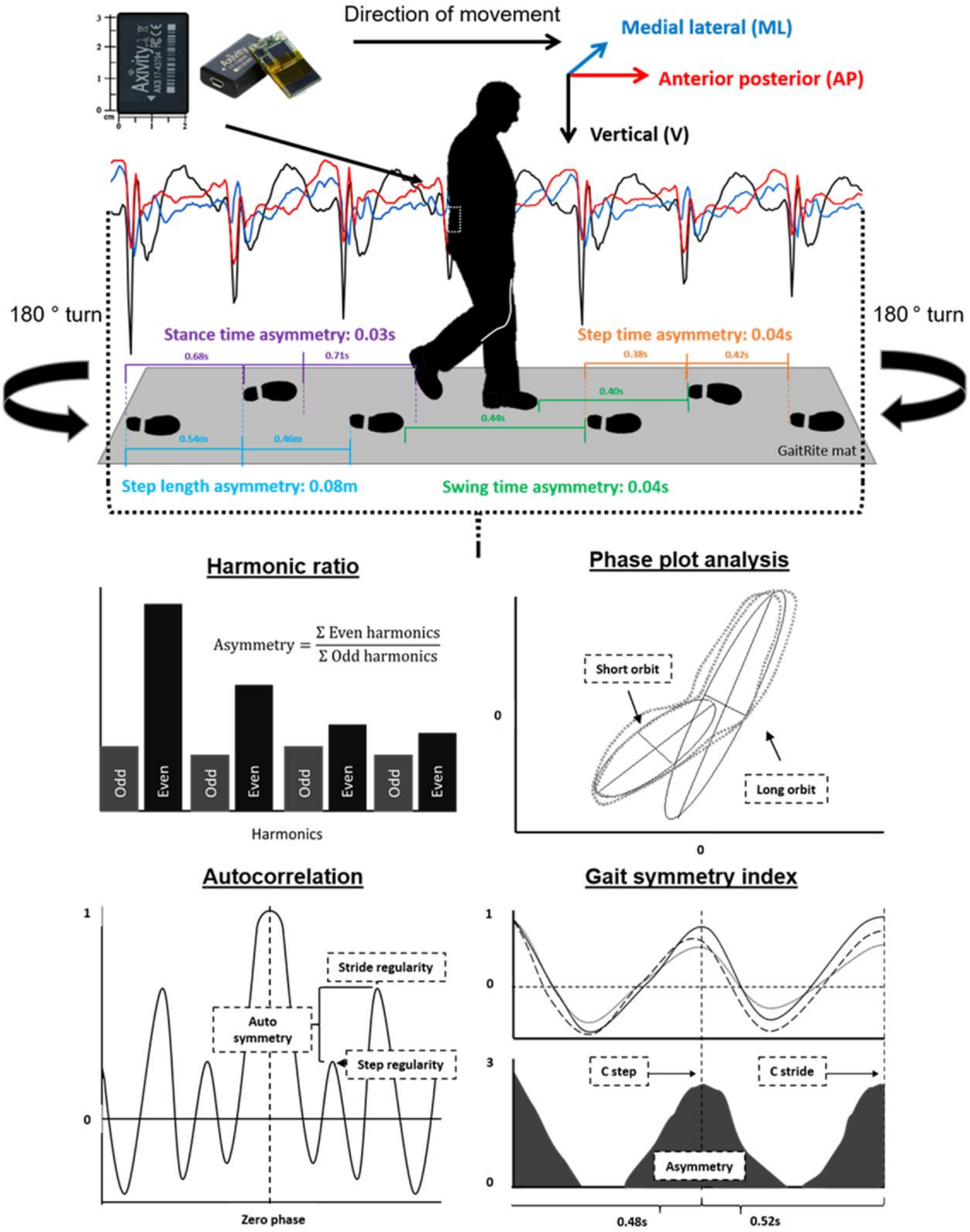


Figure 1.3.1 Indication of the instrumentation and the protocol used to collect the acceleration signal and the asymmetry parameters [5].

Note: Indication of the instrumentation and the protocol used to collect the acceleration signal and the asymmetry parameters from the GaitRite mat. Also pictured is the acceleration-derived asymmetry variables and the means for the calculation of asymmetry following the processing of the raw acceleration signal [5].

1.4 The Developing Foot in Gait Biomechanics

1.4.1 Foot Structure, Arch Function, and Load Distribution

The human foot is structurally complex, containing many bones and joints and an intricate network of soft tissue elements. Because of this complexity, small differences in foot structure can create measurable differences in function. Adult studies have long recognized that foot type is associated with biomechanical differences and with certain injury risks [6]. In children, these relationships become even more important, because the foot is still forming: foot size increases rapidly, bones ossify, soft tissues change composition, and arches develop.

The arch—particularly the medial longitudinal arch—is often described as a mechanical and functional “core” of the foot, helping to manage loads and support efficient locomotion. In general terms, arch structures contribute to distributing pressure, absorbing shock, storing and returning elastic energy, and stabilizing the foot during stance. In childhood, arch development is dynamic. There is evidence that foot development is especially rapid across school-aged years, and that arch height changes show age- and sex-related patterns [6]. Although the specific trajectory may vary across individuals, the general principle is clear: as the foot develops, its mechanical behavior changes, and so does the distribution of plantar pressure and the dynamics of gait.

1.4.2 Plantar Pressure as an Indicator of Foot Function

Plantar pressure measurement provides a direct and clinically interpretable representation of how loads are distributed under the foot during stance. It is widely used in biomechanics and clinical contexts because it is sensitive to both structural factors (e.g., arch height and foot morphology) and functional factors (e.g., movement strategy and balance control). Studies in children show associations between foot shape/arch measures and plantar pressure patterns during walking and running, reinforcing the idea that foot morphology influences functional loading (Figure 1.4.1).

A major advantage of plantar pressure is that it can reveal not only overall loading but also region-specific patterns (heel, midfoot, forefoot, toes) and time-dependent changes across stance. This makes plantar pressure particularly useful for studying developmental transitions, such as the shift from flat-foot contact toward heel-to-toe rollover, and for studying whether loads are distributed symmetrically between left and right feet.

At this point, we can already see a broader study rationale emerging: (i) Early development produces large changes in gait mechanics and foot function. (ii) Foot structure and plantar loading patterns evolve with age and experience. (iii) Symmetry is often used as an indicator of mature control, but real-world tasks (e.g., turning) and factors such as limb dominance can alter symmetry. (iv) Special populations (e.g., sensory processing disorders) may show distinct loading patterns and balance strategies.

Therefore, the gait symmetry, especially in plantar loading and in joint-level biomechanics, as well as its development, changing with task demands, and difference in children with sensory processing difficulties, were the themes that converged on a central question.

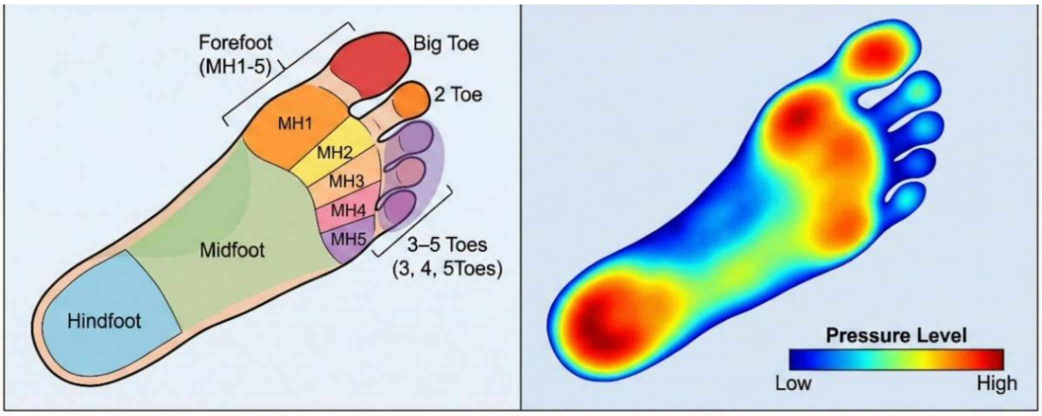


Figure 1.4.1 Foot regions and plantar pressure metrics [5].

1.4.3 Structural Maturation of the Pediatric Foot

A central reason why gait biomechanics changes so markedly during early development is that the foot itself is developing as a load-bearing structure. Unlike many other segments, the foot is not simply a rigid lever. It is a highly articulated, deformable system whose mechanical behavior depends on the evolving properties of bones, joints, ligaments, plantar soft tissues, and muscle-tendon units. In early life, ossification processes and skeletal maturation continue to reshape the foot's internal architecture. The timing and sequence of ossification centers in the foot provide an anatomical foundation for why foot stiffness, joint constraints, and segmental alignment can change across infancy and early childhood [7]. These developmental changes are not only anatomical details; they alter the functional role of the foot in gait, including how impact is attenuated, how loads are transmitted, and how propulsion is generated.

Among all structural features, the development of the foot arch, especially the medial longitudinal arch, is often emphasized because it reflects and contributes to functional maturity. Classic work describing the development of the child's arch indicates that the arch is not fully formed at the onset of walking and develops progressively over time [8]. In functional terms, a more mature arch supports load distribution across the foot, contributes to elastic energy storage and return, and helps maintain efficient rollover mechanics during stance. Conversely, in the earlier stages, when arch function is limited and plantar soft tissue composition differs, loads may distribute differently across the plantar surface, and the foot may behave more like a compliant platform than an efficient lever. This developmental perspective is important for interpreting plantar loading patterns: plantar pressure is not merely a "measurement" of gait; it is also a functional marker of how the developing foot interacts with the ground. In typical development, it is reasonable to expect systematic changes over time in (i) the location of peak pressures, (ii) the timing of regional loading, (iii) the center-of-pressure (COP) progression pattern, and (iv) the relative contribution of rearfoot, midfoot, and forefoot to support and propulsion. Understanding these features provides a biomechanical rationale for monitoring foot loading in children and for using plantar pressure to detect potentially atypical development (Figure 1.4.2).

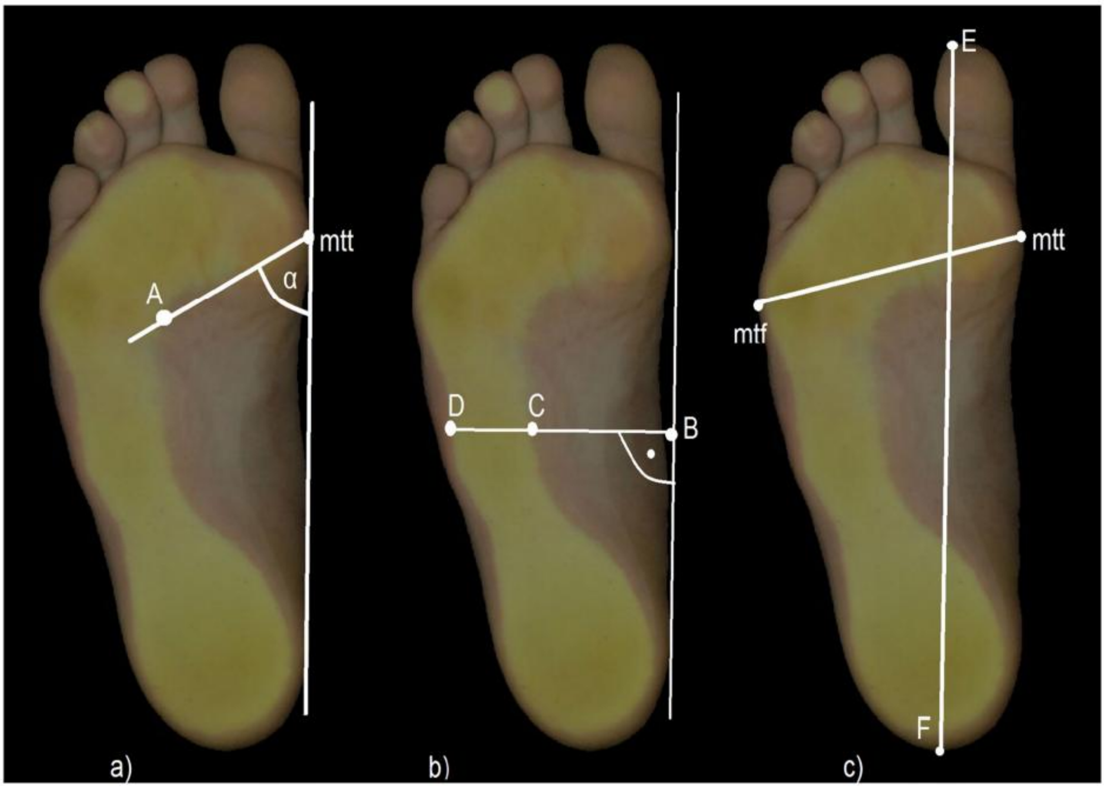


Figure 1.4.2 The method of determining the foot indicators on 2D footprint.

Note: a) Clarke’s angle, b) Sztriter-Godunov index, c) Wejsflog index. Source [8].

1.4.4 Plantar Pressure and COP Across Locomotor Tasks

Plantar pressure measurement has become a widely used tool to describe foot function during locomotion because it can quantify where and when the plantar surface is loaded, as well as how load distribution changes across tasks. In pediatric contexts, plantar pressure offers several practical advantages: it is non-invasive, interpretable in anatomical terms, and capable of capturing task-dependent changes in loading without requiring full-body motion capture. Moreover, plantar pressure can be decomposed regionally (e.g., heel, midfoot, metatarsal heads, hallux/toes), providing insight into how different parts of the foot contribute to stance.

Recent work applying dynamic pedobarographic in typically developing children demonstrates the feasibility and value of characterizing plantar pressure patterns during gait [9]. Such studies reinforce that plantar pressure patterns can serve as functional signatures of development and can reveal subtle differences that may not be obvious from spatiotemporal measures alone.

A related metric is the COP trajectory. COP progression during stance reflects the net location of ground reaction force under the foot and is therefore linked to both foot rollover mechanics and dynamic balance control. Even when two individuals show similar overall walking speed and cadence, their COP trajectories may differ in ways that reflect differences in stability strategy, foot posture, or task demands. The COP can thus be treated as an intermediate-level “control outcome”: it is the result of neuromuscular activation, joint control, and foot–ground interaction.

Importantly, plantar loading and COP are not fixed characteristics; they change with locomotor task. Straight-line walking tends to show relatively consistent rollover progression, whereas tasks such as turning impose additional constraints. Turning requires rapid reorientation of the body's movement direction and thus changes the distribution of forces under the feet. Evidence from turning studies indicates that plantar pressure patterns can shift during turning maneuvers, and that such shifts may occur early in the approach step and evolve through the turning phase [10]. The implication is that turning provides a mechanically and control-demanding context in which latent asymmetries or compensatory strategies may become more observable than during straight-line gait. This matters for developmental biomechanics because children's balance and coordination are still maturing. In typical development, gait patterns become more stable and efficient across time, but increased task demands can still expose deficits in interlimb coordination or balance strategy. Plantar pressure and COP analysis therefore offers a practical route for probing how children manage these demands.

1.5 Gait Symmetry, Asymmetry, and Limb Dominance

1.5.1 Gait Symmetry and Maturation

In many clinical and research contexts, “mature” gait is associated with relatively high bilateral consistency across left and right limbs. This is because a stable, well-coordinated gait pattern tends to exhibit consistent timing and similar magnitudes of kinematics and kinetics across sides when averaged across steps. Symmetry is therefore often treated as a surrogate marker of neuromuscular maturity, balanced strength, and robust motor control.

However, it is increasingly recognized that perfect symmetry is not the norm, even in healthy populations. Small inter-limb differences may reflect limb dominance, functional specialization, or context-specific strategy rather than impairment. The key question is not whether asymmetry exists, as it almost always does, but rather the type of asymmetry present, its magnitude, the task demands under which it occurs, and its associated functional consequences.

This point is especially important in pediatrics. Children are developing; thus, variability and mild asymmetry may be expected as part of learning and refinement. At the same time, persistent or task-amplified asymmetry could indicate developing imbalance in motor control or emerging risk factors for musculoskeletal problems. The interpretive challenge is to distinguish developmentally typical asymmetry from asymmetry that is unusually large, persistent, or associated with abnormal loading patterns.

1.5.2 Developmental Changes in Gait Symmetry

Longitudinal evidence suggests that gait symmetry tends to improve in childhood. For example, a multi-year follow-up study of foot loading data reported that gait symmetry improves across childhood, indicating a developmental trend toward more balanced plantar loading [11]. This is consistent with the idea that with increasing experience and maturation, children converge toward more consistent interlimb coordination and more stable load distribution.

Yet “symmetry” depends heavily on how it is measured. A symmetry index derived from step length may behave differently from a symmetry index derived from peak plantar pressure, COP trajectory, or joint moment profiles. Even within plantar pressure, the symmetry of total contact area may differ from the symmetry of regional impulses or peak pressures. Therefore, a mature scientific approach must treat symmetry as metric-specific, not as a single scalar property of gait.

Supporting this, studies in walking symmetry demonstrate that symmetry indices can be speed-dependent and index-dependent [12]. That is, whether gait appears symmetric can change as speed changes, and the conclusion may also change depending on which symmetry metric is used. This has direct implications for pediatric gait: children naturally walk and run at different speeds depending on age, leg length, and task instruction; therefore, comparing symmetry across children or across tasks requires careful control or statistical treatment of speed effects.

In this study context, these points motivate two methodological principles: (i) When investigating symmetry/asymmetry, it is essential to examine time-dependent profiles (e.g., COP trajectory across stance, plantar force curves) rather than relying solely on single-point summary values. (ii) It is essential to compare symmetry across multiple task conditions (e.g., walking vs. running vs. turning), because asymmetry may be subtle in simple tasks but amplified in demanding tasks.

1.5.3 Limb Dominance and Plantar Loading Asymmetry

One widely discussed contributor to asymmetry is limb dominance (or foot preference). In human movement, dominance can influence which limb is preferentially used for stabilization versus propulsion, or for skillful tasks versus support tasks. Evidence suggests that limb dominance can affect the symmetrical distribution of plantar loading during walking and running [13]. This implies that even in healthy individuals, the left and right feet may not share load identically, and the degree of asymmetry may depend on how the movement is organized and which limb tends to take a leading role.

In children and adolescents, dominance-related effects may be especially salient because neuromuscular control is still developing and because many children engage in sports and play activities that reinforce unilateral preferences. Importantly, dominance-related asymmetry may not be inherently negative. It may reflect a functional organization of movement. However, if a dominance pattern leads to persistently elevated loads in particular foot regions or consistently altered COP trajectories, it could contribute to cumulative stress or to the development of foot posture deviations over time.

At the same time, foot structure differences—such as those observed among different foot types—can also influence loading and functional mechanics [6]. While much of the foot-type literature focuses on adult or clinical populations, the general principle that structural alignment is associated with biomechanical loading is relevant when considering developmental loading symmetry and the risk that persistent asymmetry might interact with morphology during growth (Figure 1.5.1).

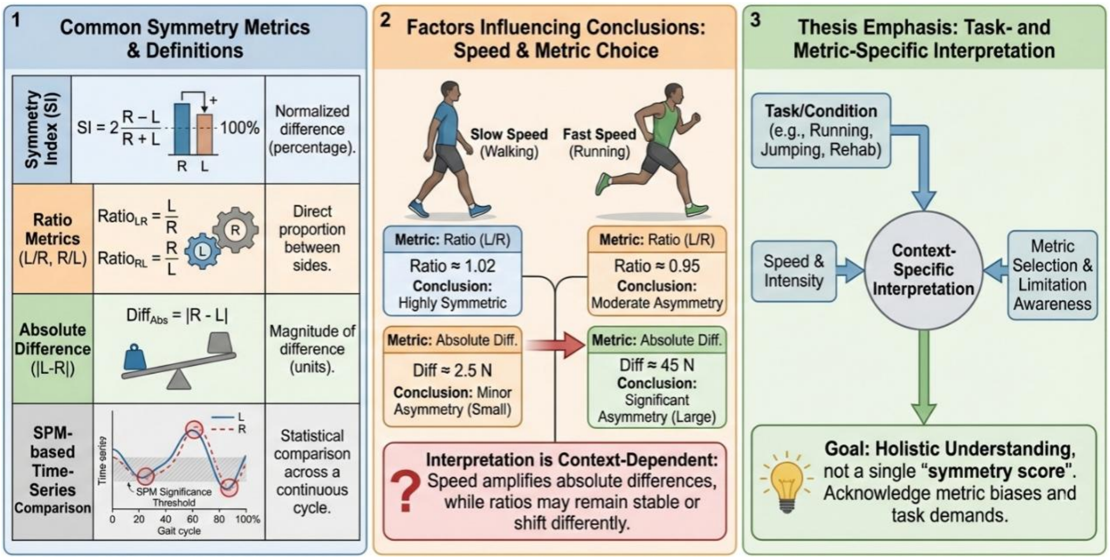


Figure 1.5.1 Symmetry vs. asymmetry: metrics and interpretation.

1.6 Turning-Induced Constraints on Gait Control and Symmetry

1.6.1 Mechanical and Neural Control Requirements of Turning

Straight-line walking can be considered a relatively repetitive, steady-state behavior in which step-to-step dynamics are similar across cycles. Turning, in contrast, is a non-repetitive or less repetitive maneuver that requires reorientation of the body's trajectory. This introduces additional mechanical demands: the locomotor system must redirect the COM velocity vector, manage centripetal requirements, and coordinate foot placements to achieve directional change while avoiding instability.

From a functional perspective, turning is ubiquitous: children turn frequently during play, daily locomotion, and sports. Yet turning is biomechanically distinct from straight walking because it often creates a division of labor between the inside limb (relative to the turn) and the outside limb. The inside limb may play a stabilizing or pivot-like role, while the outside limb may contribute more to propulsion or redirection depending on the strategy used. Even without detailing all possible turning strategies, the fundamental point is that turning tends to increase the likelihood that left–right mechanics will differ.

Consistent with this, plantar pressure studies have reported that turning can alter plantar pressure patterns, with shifts detectable during the approach phase and evolving through the turning phase [10]. Such findings support the idea that turning tasks can reveal features of dynamic stability and interlimb coordination that may be less apparent in straight-line gait. Therefore, turning is widely considered a sensitive context for probing gait control, especially in populations where balance and neuromuscular coordination are still developing or may be compromised.

1.6.2 Developmental Modulation of Turning Asymmetry

From a developmental viewpoint, turning can be seen as a task that increases the "difficulty level" of locomotion. A child who appears to walk symmetrically in straight-line walking may still show asymmetry during turning because the task requires faster online adaptation, refined postural control, and rapid redistribution of plantar loads. In addition, turning may interact with limb dominance: a child may prefer turning in one direction or rely more on one limb during directional change. If so, turning might amplify the functional consequences of dominance-related asymmetry.

These considerations provide a strong rationale for systematically investigating plantar loading and COP differences between the left and right feet in children across a set of everyday locomotor maneuvers, including walking, running, and turning. If asymmetry is task-dependent, then straight-line assessment alone may underestimate the degree of asymmetry that children experience during real-world locomotion.

1.7 Joint stress response

At this stage of the Introduction, a coherent logic begins to emerge. Typical development involves rapid changes in gait mechanics and foot function as a result of anatomical maturation (e.g., ossification [7], arch development [8]) and motor learning. Plantar pressure and COP provide functional windows into these changes [9]. Meanwhile, symmetry is often viewed as a hallmark of maturity, but it is metric-dependent and sensitive to speed and task context [12]. Turning increases mechanical and control demands and can shift plantar pressure patterns [10], making it a sensitive test for revealing asymmetry. Limb dominance further contributes to asymmetry even in healthy gait [13].

These considerations naturally lead to two applied extensions: (i) Task-demand asymmetry surveillance in healthy children and adolescents. Even if overall development tends toward improved symmetry [11], task demands such as running and turning may still elicit measurable asymmetry. Understanding when and how such asymmetry appears is important for interpreting "normal" asymmetry and for identifying unusual patterns that may warrant attention. (ii) Understanding how sensory-motor processing challenges reshape gait and plantar loading. If sensory information contributes to balance and online motor control, then disorders affecting sensory processing may alter gait strategy, especially in demanding tasks. This makes it essential to examine special populations such as children with sensory processing difficulties.

This second extension is particularly important because developmental disorders do not merely delay "normal" development; they can also produce qualitatively different movement strategies. These strategies may be visible in plantar loading and balance-related variables, and they may be most evident during high-demand tasks such as running and turning.

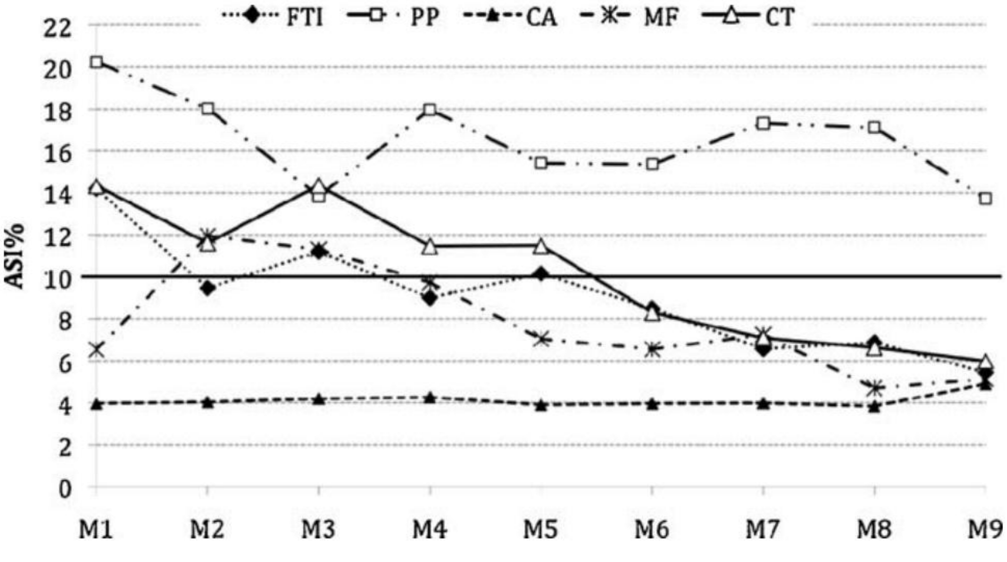


Figure 1.6.1 ASI% of the peak pressure (PP), contact area (CA), contact time (CT), relative maximum force (MF) and the force-time integral (FTI) during 4 years in children [11].

1.8 Sensory Contributions to Gait Control

Although gait is often described using mechanical terms (e.g., inverted pendulum dynamics in walking, spring-mass behavior in running), locomotion is fundamentally a sensorimotor behavior. The nervous system must continuously estimate body state (segment orientation, velocity, COM motion), anticipate upcoming events (foot contact timing, load acceptance), and update motor commands based on sensory feedback. In adults, many of these processes occur with a high degree of automaticity; yet even in adults, gait control can be disrupted by altered sensory input, environmental perturbations, or increased task demands such as turning or rapid changes of direction.

The relevance of sensory control becomes particularly clear in children. Early locomotion is not just the execution of a stable motor program; it is an evolving skill in which the child must learn how to interpret sensory information and transform it into effective motor control. Postural control maturation—especially the ability to regulate gravity-related forces—develops over the first years of walking and contributes to improvements in gait stability and efficiency [4]. When postural control is still immature, the child often relies on conservative strategies (wide step width, long double support) that reduce the need for precise rapid corrections. As sensory integration improves, children can adopt more economical strategies and maintain stability with less reliance on conservative margins.

From a biomechanics viewpoint, this sensory involvement can be described as feedback–feedforward interplay. Feedforward components include anticipatory adjustments that prepare the body for expected loads and transitions, whereas feedback components include rapid corrections to deviations in balance or unexpected load distributions. In tasks such as turning—where demands on online motor control increase—this interplay becomes more critical. Turning requires rapid reorientation of the body's motion direction and may compress the time window in which the nervous system must detect and respond to instability. This is one reason turning is often considered a "stress test" for gait control and interlimb coordination [10].

If sensory integration is compromised, the locomotor system may adopt strategies that prioritize perceived safety at the cost of efficiency or normal loading distribution. Such strategies may include reducing joint range of motion, stiffening segments, increasing co-contraction, or shifting load distribution to more mechanically stable regions of the foot. These adaptations are particularly relevant when considering developmental disorders in which sensory processing is atypical (Figure 1.8.1).

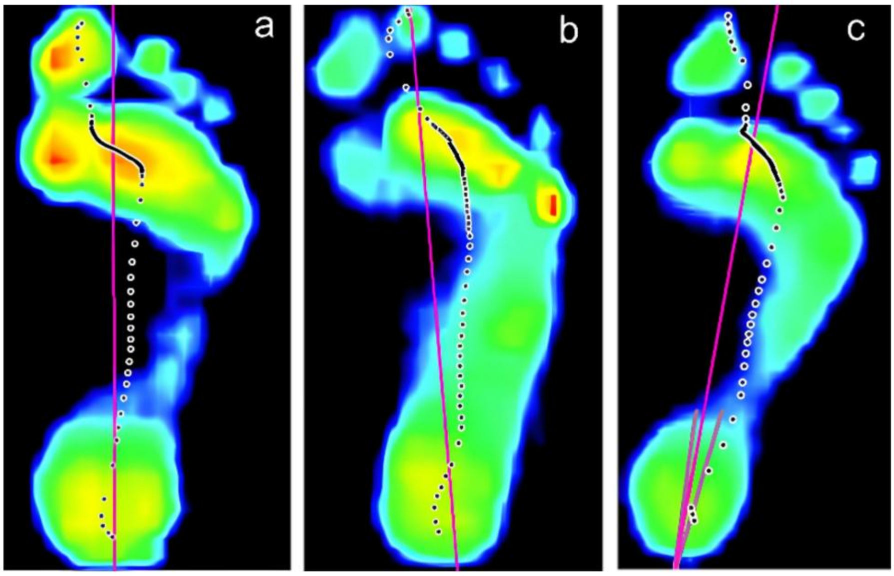


Figure 1.8.1 Classifications of plantar pressure characteristics.

Note: a) represents the thumb extension type, b) represents the midfoot-lateral forefoot push-off type, and c) represents the normal type [10].

1.9 Sensory Processing Disorder and Locomotor Development

1.9.1 Sensory Processing Disorder

Sensory Processing Disorder (SPD) refers to atypical sensory modulation, discrimination, and/or sensory-based motor functioning that affects how individuals receive, interpret, and respond to sensory stimuli. In school-aged children, sensory processing difficulties are increasingly recognized as clinically relevant and are frequently discussed in relation to developmental profiles that may overlap with or co-occur with other neurodevelopmental conditions. Although prevalence estimates vary across studies and definitions, sensory over-responsivity has been reported as a meaningful concern in childhood populations, with implications for social-emotional correlates and day-to-day function [14].

The key relevance of SPD to gait biomechanics is straightforward: locomotion depends not only on musculoskeletal capacity but also on sensory feedback and the ability to integrate sensory inputs into stable movement. Children with sensory processing difficulties may show challenges in balance, postural control, motor planning, or responses to environmental changes. As a result, the biomechanical patterns of their gait—especially under higher dynamic demands—may deviate from those of typically developing peers.

1.9.2 Task Demands and Gait Alterations in Sensory Processing Disorder

A critical observation in pediatric motor behavior is that the “difficulty” of a locomotor task is not fixed. Straight-line walking at self-selected speed may be manageable for many children, including some with sensory processing challenges, because it is relatively predictable, mechanically less demanding, and can be stabilized using conservative strategies such as wider steps, slower progression, and reduced movement excursions. Under these conditions, longer stance times and smaller destabilizing forces allow the locomotor system more time to accommodate variability in sensory processing without obvious disruption of gross gait appearance.

However, running and turning introduce additional demands that reduce this compensatory margin. Running shifts the mechanism from pendulum-like energy exchange toward spring-mass behavior, increasing the importance of elastic energy management, rapid force modulation, and precise timing. Turning requires deceleration and acceleration in a new direction, rapid COM redirection, and rapid redistribution of plantar loads [10]. In both cases, the time available to detect instability and update motor output is reduced, while the mechanical perturbations acting on the body are increased. As a result, sensory integration challenges that may remain masked during simple gait are more likely to become functionally visible when locomotion requires faster online control.

This distinction is important for interpreting SPD-related gait behavior. A child with sensory processing difficulties may appear to walk normally in a simple corridor because low-demand walking permits stability-preserving compensations. By contrast, during running, the locomotor system must rely more heavily on precisely timed sensory feedback to regulate foot loading, maintain balance, and coordinate push-off. If sensory integration is less efficient, children may adopt strategies that prioritize stability over efficiency, such as limiting rapid distal push-off, reducing medial–lateral foot modulation, or maintaining a flatter, more cautious loading pattern. Therefore, one should not assume that a child who “walks normally” in a simple corridor will show equally typical control during turning and running. In fact, higher-demand tasks are often more diagnostic for revealing latent deficits in dynamic balance or interlimb coordination.

1.9.3 SPD and the broader study rationale

Within the logic of this study, SPD represents a strategically important “contrast condition” because it allows us to probe how atypical sensory integration reshapes the biomechanics of gait, plantar loading, and balance strategies in a way that cannot be inferred from typical development alone. While typical development trends toward improved stability and symmetry across childhood [11], SPD may disrupt or alter that trajectory—not necessarily by producing obvious abnormalities during low-demand gait, but by changing how children allocate control resources when task constraints intensify. In other words, SPD is not introduced here as a simple “impaired versus unimpaired” comparison; rather, it is used to test a mechanistic proposition: that the quality and reliability of sensory integration fundamentally constrains the strategies available for maintaining dynamic stability, and that these constraints become most visible when locomotor tasks require rapid updating of body state and rapid redistribution of plantar loads.

A central premise motivating this rationale is that gait is not merely a repeating mechanical pattern. Even in straight-line walking, the locomotor system must continuously regulate the body’s center of mass relative to a moving base of support by coordinating segment motions, managing stance-to-swing transitions, and maintaining a stable margin against perturbations. Classic gait descriptions emphasize the cyclical structure of stance and swing and the range of clinically meaningful variables that can be derived from these phases (e.g., spatiotemporal parameters, joint kinematics, and kinetics) [1]. However, the stability of this cycle depends on the nervous system’s capacity to estimate body state and update motor output using multisensory feedback. In childhood, this estimation-and-control problem is further complicated by growth, changing segment inertias, and ongoing maturation of postural control systems. As postural control develops, children progressively refine how they regulate gravity-related forces and reduce reliance on conservative stability strategies [10]. This developmental frame is essential, because it implies that “typical” gait is a moving target across age, and that deviations may be best interpreted not as static errors but as alternative solutions under different sensorimotor constraints.

SPD is particularly informative within this framework because it is defined by atypical processing of sensory information, which can include altered sensory modulation, discrimination, and sensory-based motor functioning. From a locomotor-control perspective, such atypical processing can be conceptualized as either (i) a reduction in the fidelity of sensory signals (greater noise), (ii) altered weighting or integration of sensory modalities, or (iii) reduced efficiency in translating sensory information into appropriately timed motor corrections. Importantly, these constraints do not necessarily prevent children from producing a superficially “normal” walking pattern at comfortable speeds. Straight-line walking is a relatively predictable task with longer stance times and relatively modest destabilizing forces, and it allows multiple compensations (e.g., slower progression, subtle widening of the base of support, reduced excursion) that can preserve gross gait appearance. Therefore, a critical methodological risk in SPD-related gait research is that low-demand tasks may underestimate clinically meaningful differences, because they permit stability-preserving compensations that mask underlying control limitations.

This is why task demand occupies a central role in the broader study rationale. The core question is not simply whether SPD children “walk differently,” but whether they manage the sensorimotor demands of locomotion differently, particularly when the movement environment requires rapid online control. Running and turning provide two complementary ways of increasing this demand. Running reduces the time available for within-step corrections while increasing impact and the magnitude of required force modulation, thereby amplifying the cost of delayed or imprecise feedback integration. Turning adds a different kind of challenge: it requires redirection of the center of mass velocity vector and generates asymmetrical limb roles (inside versus outside limb) that inherently increase the complexity of coordination. Turning has been shown to alter plantar pressure characteristics relative to straight gait, reflecting the additional mechanical and control requirements of reorientation [13]. In this sense, turning can be treated as a naturalistic “stress test” for locomotor control: it is ubiquitous in daily life and play, but it demands rapid reallocation of support, redirection forces, and stable foot–ground interaction under changing directions of acceleration.

The interaction of SPD with task demand is therefore expected to be non-linear. Under low demand, SPD-related differences may be subtle, intermittent, or absent, because the system can achieve stability using slower, conservative strategies that do not require rapid sensory updating. Under higher demand, however, the locomotor system must rely on precisely timed modulation of plantar loading, efficient center-of-pressure progression, and coordinated proximal–distal joint control to maintain balance while meeting performance demands. If sensory integration is atypical, one would anticipate that children may adopt strategies that prioritize perceived stability over efficiency. Such strategies might include reduced reliance on rapid distal push-off, altered medial–lateral weight transfer, or a redistribution of plantar loads toward regions that provide a mechanically “safer” contact configuration. Crucially, these strategies can be interpreted as adaptive rather than merely deficient: they may reduce the probability of instability in the short term, even if they increase mechanical cost, reduce propulsion efficiency, or alter regional tissue loading.

Limb dominance and functional asymmetry add a further dimension to why SPD is a valuable contrast condition. Even in typically developing populations, left–right symmetry is not absolute, and dominance can influence functional roles between limbs. This means that asymmetry cannot be interpreted as inherently pathological; rather, it must be interpreted relative to task context and the expected division of labor between limbs. In turning tasks, the inside and outside limbs are mechanically constrained to do different work, and in running, individuals may implicitly rely more on a preferred limb for propulsion or stabilization. These considerations imply that SPD-related differences may not present as a simple “increase in asymmetry” across all metrics. Instead, SPD may alter the organization of asymmetry: for example, SPD may reduce the ability to flexibly shift limb roles with changing tasks, or it may compress the range of adaptive medial–lateral foot control used to stabilize under dynamic conditions. Therefore, the study’s rationale explicitly includes comparisons that are sensitive to side and role (left vs. right; inside vs. outside; dominant vs. non-dominant), rather than collapsing behavior into a single symmetry score.

This leads to a key methodological implication: because “symmetry” is metric-dependent and can vary with speed and context, it cannot be adequately characterized by a single discrete outcome. Evidence indicates that walking symmetry is dependent on both speed and the specific symmetry index used [14]. Thus, if SPD influences gait through altered sensory integration, the most informative differences may appear as phase-specific or region-specific changes across the stance phase, rather than as simple differences in a single peak value. For this reason, the present study’s emphasis on plantar loading distribution and center-of-pressure behavior is not incidental. Plantar pressure and COP trajectories are direct outputs of how the neuromuscular system manages support and progression at the foot–ground interface, and they are inherently suited to capturing subtle changes in strategy. Moreover, because plantar loading reflects both structural factors (e.g., foot morphology) and control factors (e.g., balance strategy), it provides an anatomically interpretable window into how children distribute and shift load to achieve stability. In SPD, where sensory-based motor functioning is central, this interface-level evidence is especially valuable because it may reveal compensations that are not visible in gross spatiotemporal measures.

From a translational standpoint, using SPD as a contrast condition strengthens the clinical relevance of the study in two ways. First, it targets a real-world diagnostic problem: many children with sensory processing difficulties may function adequately in predictable environments but struggle in dynamic, multi-directional play and sport contexts. If biomechanical differences are primarily task-dependent, then relying on straight-line walking assessments alone could lead to under-identification of motor-control challenges that matter most for participation and safety. Second, it supports intervention logic. If SPD-related differences emerge primarily under high-demand tasks, interventions may need to prioritize dynamic balance, rapid weight transfer, and context-specific locomotor training rather than focusing exclusively on static balance or low-speed gait practice. In this way, the SPD contrast condition provides a bridge from mechanistic understanding (how sensory integration constrains locomotor control) to actionable assessment and training principles (which tasks best reveal deficits; which control components should be targeted).

In summary, SPD is incorporated into the broader study rationale as a mechanistic probe of sensorimotor constraints on gait. Typical development generally trends toward improved stability and symmetry [11], but this trend is expected to be conditional on sensory integration capacity and task demands. By systematically comparing walking, running, and turning, and by evaluating plantar loading and COP behavior as time-varying outcomes, the study is positioned to test whether SPD is associated with differences that are negligible under low demand yet amplified under dynamic constraints. This approach aligns with the broader view that gait is a context-dependent, multi-system behavior [1], that postural control maturation is a foundational component of developmental locomotion [10], that turning introduces distinctive loading and control requirements [13], and that symmetry assessments must be interpreted as speed- and index-dependent [14]. Together, these considerations justify SPD as a central contrast condition and motivate the study’s task-based, biomechanics-driven design.

1.10 Clinical Relevance of Plantar Pressure and COP in Sensory–Motor Research

1.10.1 Plantar Pressure and COP as Outcome Measures in SPD

If sensory processing affects balance and motor control, then its effects should be visible in measures that reflect how the foot is used to regulate stability. Plantar pressure distribution and COP trajectory are especially relevant because they represent direct outcomes of how the body manages support and progression during stance. When the nervous system adjusts posture and movement, it does so partly through changing how the foot contacts and loads the ground—either by shifting the COP path, redistributing load across regions, or changing the timing and magnitude of regional forces.

In addition, plantar pressure is sensitive to both structural and functional factors. On the structural side, foot type and arch properties influence loading patterns [6]. On the functional side, balance strategy and limb dominance can change plantar loading distribution even in healthy individuals [13]. Therefore, plantar pressure measures can be used not only to describe group differences but also to interpret potential mechanisms (e.g., whether a child is relying more on the lateral forefoot, whether midfoot loading is elevated, whether toe contribution is reduced).

Because SPD is associated with altered sensory integration and potentially altered balance strategies, plantar pressure and COP metrics can offer an objective and clinically interpretable window into how these children manage locomotion—especially under dynamic conditions.

1.10.2 Temporal Characteristics of Plantar Loading and Balance Control

As emphasized earlier, conclusions about gait symmetry can depend on the metric used and on speed [12]. This is equally true for SPD-related differences. A child might show similar peak pressure values but different timing of load transfer, or similar total impulse but different COP trajectories. Therefore, a major methodological implication is that time-dependent assessment—e.g., examining COP progression across stance, region-specific loading profiles across stance, and phase-specific differences—can provide richer insight than isolated summary values.

In this study, this conceptual point supports a systematic approach: analyze plantar loading across multiple tasks and interpret differences within the context of dynamic control demands (Figure 1.10.1).

1.11 Task-Dependent Asymmetry in Gait Biomechanics

A central unifying idea emerging across the literature and the four papers underpinning this study is that asymmetry is often task-dependent. Even in healthy individuals, asymmetry is frequently minimal during straight walking but increases in conditions requiring greater control, higher forces, or complex coordination. Turning is a prime example of such a condition. Studies show that plantar pressure patterns and loading strategies differ during turning compared to straight gait, and that these differences can manifest as shifts in regional loading or COP behavior [10].

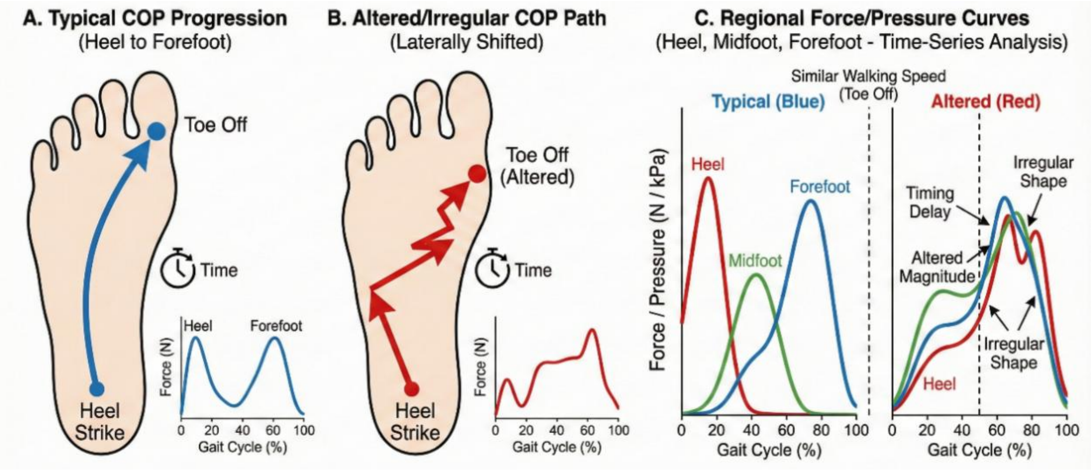


Figure 1.10.1 Example COP trajectories and plantar loading profiles.
(A) a typical COP progression from heel to forefoot, (B) a more laterally shifted or irregular COP path, and (C) example regional force/pressure curves (heel, midfoot, forefoot) illustrating how timing or magnitude can differ even if walking speed is similar.

From a developmental perspective, task dependence is especially informative. If a child’s control system is still maturing, higher-demand tasks may reveal the “weak links” in their control strategy. Similarly, if a child has sensory processing challenges, task demands may determine whether the child can maintain a relatively typical pattern or whether compensatory strategies become necessary. In this study, task-dependent asymmetry is examined at two complementary biomechanical levels: (i) Foot-level loading and COP asymmetry in children across walking, running, and turning, where plantar pressure offers a direct measure of load distribution and balance behavior. (ii) Whole-limb kinematic and kinetic asymmetry in adolescents across straight and turning locomotion, where joint-level mechanics provide a more proximal view of how asymmetry emerges across the kinetic chain. This multi-level view is important because the foot is the interface with the ground, while proximal joints (ankle, knee, hip) reflect the motor strategies used to generate and regulate motion. If a child exhibits plantar loading asymmetry, it is crucial to determine whether that asymmetry is simply a localized foot strategy or part of a broader interlimb coordination pattern.

1.12 Evidence Informing the Relevant Research Focus

1.12.1 Typical Development: Stability, Symmetry, and Variability

Typical development is often characterized by improving stability, reduced variability, and increasing symmetry. Longitudinal evidence supports the idea that gait symmetry improves across childhood [11]. Yet there are critical caveats: (i) Symmetry is not absolute; mild asymmetry can be normal and functional. (ii) Symmetry depends on task and speed [12]. (iii) Structural factors (e.g., foot type) influence load distribution [6]. (iv) Limb dominance influences plantar loading patterns even in healthy individuals [10]. These caveats mean that "typical" gait cannot be reduced to a single symmetry score and that any interpretation must be conditional on context.

1.12.2 Locomotor Tasks That Challenge Gait Control

Turning is biomechanically distinct from straight gait and tends to shift plantar loading patterns [10]. Running increases impact and elastic demands and can reveal coordination differences that are not evident in walking. In combination—e.g., running while turning—task demands are high, and asymmetry may become more pronounced. Therefore, one would predict that differences between left and right limbs, or between groups, may be minimal during walking but more observable during running and turning.

1.12.3 Sensory Processing Disorder and Task-Based Gait Evidence Gaps

While sensory over-responsivity and sensory processing difficulties have been described in pediatric populations with meaningful functional implications [14], there is comparatively limited biomechanical literature detailing how SPD reshapes plantar loading and balance behavior across everyday locomotor tasks. In particular, a task-based analysis comparing walking, running, and turning is valuable because it can clarify whether SPD-related differences are subtle and only appear under stress, or whether they are evident even in low-demand conditions.

Evidence directly addressing SPD-related plantar loading and balance behavior provides a clear motivation for this study' inclusion of SPD as a key population, and for analyzing both dominant and non-dominant limbs. The study focusing on foot loading and balance behavior in children with sensory processing difficulties supports the view that plantar loading patterns can reflect altered balance strategies and may provide clinically meaningful insight [15].

Together, these points justify a study structure that integrates: (i) typical gait development and foot function, (ii) task-dependent asymmetry in healthy children and adolescents, and (iii) SPD-related differences in plantar loading and balance.

1.13 Integrative of Development, Task Demands, and Clinical Application

The conceptual framework guiding this study can be summarized as a three-layer logic: (i) Developmental layer. Gait and foot function evolve across early childhood due to growth, ossification [7], arch development [8], and maturation of postural control [4]. This process generally trends toward more stable and symmetrical gait [11]. (ii) Task-demand layer: Symmetry is context-specific. Increased task demands (running, turning) may amplify asymmetry because they increase mechanical demands and reduce the time available for online control. Turning modifies plantar pressure patterns [10]. Speed and metric choice further influence symmetry assessments [12]. (iii) Clinical/special-population layer: Sensory processing difficulties may alter balance and movement strategy, especially under dynamic demands. Plantar pressure and COP provide a clinically interpretable window into these changes. Sensory over-responsivity and sensory processing difficulties have meaningful developmental and functional implications [14], and plantar loading/balance differences in sensory processing populations motivate targeted investigation [15]. This framework is not merely descriptive; it produces testable predictions: (i) Healthy children may show near-symmetric patterns in straight walking but greater asymmetry in turning or running tasks. (ii) Adolescents may show phase-specific asymmetry in joint mechanics that becomes more pronounced under turning conditions. (iii) SPD children may show altered plantar loading distribution and reduced balance indicators particularly during high-demand running and turning tasks, and these changes may differ between dominant and non-dominant limbs.

1.14 Research gaps

Although typical gait development has been described as a progression from highly variable, stability-oriented early walking toward more efficient and coordinated adult-like locomotion, important limitations remain in how pediatric gait is commonly characterized and interpreted. Specifically, the following research gaps can be identified:

(1) First, typical pediatric gait is still commonly characterized under simplified straight-line laboratory conditions, despite the fact that developmental locomotion is inherently dynamic and multi-directional. Developmental studies emphasize that early walking is accompanied by rapid improvements in balance and postural regulation, while other elements—such as interlimb coordination and refined control—continue to mature across childhood [4,16]. At the same time, foot maturation (including ossification processes and arch development) changes the mechanical behavior of the foot–ground interface, which should be reflected in plantar loading patterns across growth [7–8]. However, many discussions of "typical gait" still rely heavily on straight-line walking under laboratory constraints, whereas children's real-world locomotion is inherently multi-directional and includes frequent turning, acceleration, and deceleration.

(2) Second, gait symmetry remains insufficiently defined in relation to metric choice, speed, and functional context. Longitudinal observations indicate that symmetry tends to improve across childhood [11], but symmetry is also known to be metric-dependent and speed-dependent [12]. Moreover, even in healthy people, limb dominance can influence plantar load distribution [13], and broader reviews emphasize that small asymmetries can be normal and functional rather than pathological [17]. This means that the presence of asymmetry alone is not sufficiently informative; rather, researchers must identify which metrics show asymmetry, when in the stance phase, and under which tasks.

(3) Third, the role of task demand—especially turning—remains underexplored in pediatric gait biomechanics. Turning is widely recognized as a locomotor condition that increases control requirements, redistributes plantar loading, and can amplify left–right differences [10]. Biomechanically, turning requires COM redirection and can involve distinct inside–outside limb roles, which introduces asymmetries even in healthy gait [18]. In children, turning gait has its own characteristic spatiotemporal and kinematic features and may reveal coordination constraints not apparent in straight-line walking [19]. Yet systematic comparisons of left–right plantar loading profiles across walking, running, and turning in children remain limited, particularly when analyses consider the full-time course (e.g., COP trajectory) rather than only discrete summary values.

(4) Fourth, evidence remains insufficiently integrated across biomechanical measurement levels. Plantar pressure and COP describe the foot–ground interaction, but asymmetry may also

originate proximally (ankle, knee, hip mechanics). Without joint-level evidence, it is difficult to determine whether plantar-loading asymmetry reflects local foot strategy, whole-limb control differences, or task-specific coordination patterns along the kinetic chain. Time-series approaches such as one-dimensional statistical parametric mapping are increasingly used to identify phase-specific differences across a cycle, providing a powerful alternative to single-point comparisons [20].

(5) Finally, the biomechanical consequences of sensory processing differences during everyday locomotor tasks remain comparatively under-characterized. Although sensory processing differences have been increasingly recognized as developmentally meaningful and functionally relevant [14], biomechanical evidence describing how sensory processing challenges shape plantar loading and dynamic balance in everyday locomotor tasks remains comparatively sparse. Epidemiological and conceptual work emphasizes that sensory processing problems can influence participation and motor behavior in childhood and calls for translational research that links mechanisms to functional outcomes [21–23]. Clinically, plantar pressure is already recognized as useful for quantifying gait characteristics in pediatric disorders (e.g., cerebral palsy) [24], suggesting a strong rationale for applying similar approaches to sensory processing populations in task-demanding contexts.

Taken together, these gaps indicate that pediatric gait asymmetry should not be interpreted as a single static feature, but rather as a developmental, task-dependent, and multi-level phenomenon with potential clinical relevance. Accordingly, this study was designed with the following objectives:

(1) to characterize how plantar loading and COP reflect developmental gait asymmetry in typically developing children;

(2) to determine how task demand, particularly running and turning, modifies interlimb asymmetry across locomotor conditions;

(3) to integrate foot-level and joint-level biomechanical evidence in order to clarify whether asymmetry reflects local loading strategy, whole-limb control, or task-specific coordination;

(4) to examine whether children with sensory processing difficulties exhibit distinct plantar loading and balance-related adaptations, particularly under dynamic task demands.

1.15 Study Approach and Hypotheses

Building on the research gaps and objectives outlined above, this study establishes a unified developmental biomechanics framework for examining how gait asymmetry is expressed across developmental stages, locomotor tasks, and sensory–motor contexts. Within this framework, the narrative synthesis and the empirical investigations are positioned as complementary components of a single coherent line of argument. The narrative synthesis provides the conceptual and interpretive foundation by consolidating what is known about typical toddler gait development, the maturation of stability control, and the evolving role of the foot and arch during early locomotion. It is used primarily to support the Introduction and Discussion, ensuring that the empirical findings are interpreted against a clear developmental baseline rather than compared implicitly with adult gait or with isolated metrics.

On this developmental foundation, the empirical components provide complementary evidence about how symmetry/asymmetry is expressed under different constraints. Instead of treating symmetry as a single number, this study focuses on task-specific and phase-specific differences. This addresses the metric-dependence of symmetry [12,17] by emphasizing time-dependent measures such as COP progression and regional loading profiles rather than relying solely on peak values. The inclusion of turning tasks explicitly targets the task-demand gap: turning is treated as a natural “stress condition” that is expected to redistribute plantar loading and reveal interlimb differences that are not observable in straight walking [10,18–19]. Normative pedobarographic references in typically developing children further support interpretation of what constitutes expected patterns across childhood [9,25–27].

Crucially, this study integrates evidence across levels of analysis. Foot-level loading and COP outcomes are interpreted alongside joint-level asymmetry evidence (particularly in adolescents), enabling mechanistic reasoning about whether asymmetry reflects local foot behavior, proximal control, or task-specific limb roles. Methodologically, time-series approaches (including SPM-based reasoning [20]) are used to identify where within stance differences emerge, which supports more precise interpretation than a single averaged outcome.

Finally, this study extends from typical development into translational relevance by including sensory processing populations. By examining sensory processing differences under everyday task conditions (walking, running, turning), and by linking differences to balance-related outcomes inferred from COP and loading distribution, this study addresses the clinical gap highlighted in sensory processing literature calling for translational links between sensory mechanisms and functional motor outcomes [14,21–23]. This approach leverages plantar pressure as a clinically interpretable measure that has proven value in other pediatric movement disorders [24].

Based on developmental evidence that gait stability and symmetry improve through childhood [4,11,16], combined with evidence that symmetry is speed- and metric-dependent [12] and influenced by dominance [10,17], this study advances the following core hypotheses.

(1) First, healthy children and adolescents will exhibit measurable interlimb differences even during straight-line tasks, but these differences will generally be small and dependent on the chosen metric (H1). This aligns with the broader view that minor asymmetry can be normal in able-bodied gait [17] and that symmetry indices can change with speed and index definition [12].

(2) Second, asymmetry will increase under higher task demands (H2). In particular, running and turning will amplify left–right differences in plantar loading and COP trajectories compared with straight walking, because turning redistributes plantar pressure patterns and requires rapid COM redirection and limb-role differentiation [10,18–19]. The same logic predicts that adolescents will show more pronounced and phase-specific joint-level asymmetries during turning tasks than during straight-line gait (H3), reflecting task-dependent coordination along the kinetic chain and the need for rapid stabilization and redirection.

(3) Third, children with sensory processing difficulties will demonstrate altered plantar loading strategies and reduced balance-related indicators, especially during dynamic running and turning conditions (H4). This hypothesis is consistent with work showing altered foot loading and balance behavior in sensory processing populations [15] and with conceptual and epidemiological literature emphasizing that sensory processing differences can affect functional behavior and warrant translational mechanistic study [14,21–23]. This study further anticipates that group differences may be subtle in simple walking but become more evident as task demands increase.

1.16 Value and Practical Significance

This study has significance at three levels: developmental biomechanics theory, methodological advancement in gait asymmetry characterization, and translational relevance for pediatric assessment and rehabilitation.

From a theoretical standpoint, the study clarifies symmetry as a developmental achievement that remains context-dependent. It integrates knowledge about postural control maturation [4], typical gait refinement toward adult-like patterns [16], and the evolving mechanical role of the foot and arch across growth [7–8]. By placing turning and running at the center of analysis rather than treating them as optional add-ons, the study aligns gait research with real-world locomotor demands and strengthens developmental interpretations of stability and coordination.

Methodologically, the study advances a time-resolved interpretation of asymmetry. Because symmetry can vary with speed and index [12], and because normal gait can contain functional asymmetries [17], a key contribution is to emphasize phase-specific and task-specific differences using time-series logic, supported by modern approaches such as SPM-based reasoning [20]. This offers a more precise basis for describing when and where asymmetry emerges (e.g., early vs. late stance; COP path shifts), which is essential for mechanistic explanation and for guiding targeted interventions.

Translationally, the study provides a framework for interpreting plantar pressure and COP outcomes as clinically meaningful indicators of balance strategy and locomotor control. Normative pedobarographic characterization in children supports the identification of expected ranges and patterns [9,25–27], while the inclusion of sensory processing populations addresses a pressing need identified in sensory processing literature for translational links between sensory mechanisms and functional outcomes [14,21–23]. Because plantar pressure measures have demonstrated clinical value in pediatric disorders such as cerebral palsy [24], extending task-based plantar loading analysis to sensory processing populations can support future screening, individualized training, and rehabilitation planning. Ultimately, the study aims to help clinicians and researchers distinguish typical task-amplified asymmetry from patterns that may indicate elevated risk or atypical motor control, while recognizing that asymmetry must be interpreted in relation to task demand, metric choice, and developmental stage.

2. Materials and methods

2.1 Participant

2.1.1 Rationale for cohort composition and between-group comparability

The three cohorts were recruited to address related but analytically distinct questions within the overall framework of this study. Group A provided a homogeneous sample of typically developing children for characterizing plantar loading asymmetry during walking, running, and turning under developmental conditions. Group B was designed as a clinical comparison within the same sex and a similar age range; therefore, both the SPD subgroup and the control subgroup were restricted to boys so that between-group differences could be interpreted primarily in relation to sensory processing status rather than sex-related variability. Group C provided a separate homogeneous adolescent cohort for joint-level kinematic and kinetic analysis during higher-demand locomotor tasks.

Accordingly, the cohort structure was intended to preserve within-cohort comparability rather than to support direct statistical comparison across all three groups. Table 2.1.1 therefore provides descriptive characteristics of the total sample, whereas inferential analyses were conducted within each cohort-specific design: left–right comparisons in Groups A and C, and SPD-versus-control comparisons in Group B. This design reduced heterogeneity within each analytical comparison and improved internal validity for the specific question addressed by each cohort.

2.1.2 Participant recruitment

This study recruited participants across three related but analytically distinct cohorts. Group A consisted of 15 healthy female children (mean age 7.0 ± 1.3 years, height 128.4 ± 6.9 cm, weight 23.2 ± 3.8 kg). Group B included 12 male children divided evenly into a SPD group and a control group – the SPD subgroup (n = 6, age 5.83 ± 1.17 years, height 112.3 ± 7.8 cm, weight 19.5 ± 4.4 kg) and age-matched healthy controls (n = 6, age 7.1 ± 1.2 years, height 134.2 ± 5.7 cm, weight 24.1 ± 3.1 kg). Group C comprised 15 healthy male adolescents (mean age 15.4 ± 1.05 years, height 160.6 ± 6.1 cm, weight 50.8 ± 5.3 kg). All participants were free of any lower-limb injury or surgery in the 6 months prior to testing. The baseline information was listed in Table 2.1.1. The dominant leg for each individual was determined by their preferred foot for kicking a ball, with all participants identified as right-leg dominant. Before data collection, participants (and guardians when relevant) were informed of the experimental procedures and provided written consent. All procedures conformed to the Declaration of Helsinki, and ethical approval was obtained from the Ningbo University ethics committee (ethics codes RAGH20201216 for Group B; TY2024022 for Group C).

Table 2.1.1 Anthropometric characteristics of the recruited participants

Items	Group A (n=15)	Group B		Group C (n=15)	Total (N=42)
		SPD (n=6)	Control (n=6)		
Age (years)	7.00±1.30	5.83±1.17	7.10±1.20	15.40±1.05	9.85±4.36
Height (cm)	128.4±6.9	112.3±7.8	134.2±5.7	160.6±6.1	138.4±19.0
Weight (kg)	23.2±3.8	19.5±4.4	24.1±3.1	50.8±5.3	32.7±14.4
BMI (kg/m^2)	14.1	15.5	13.4	19.7	17

2.2 Experimental Protocol

All testing was performed with participants barefoot to eliminate footwear influences. Each participant completed a series of gait tasks on a 20-m walkway at a self-selected comfortable speed. The tasks included: (i) straight walking on level ground; (ii) straight running; (iii) 90° turning while walking (to both left and right directions); and (iv) 90° turning while running (to left and right). For turning trials, participants approached a designated turning point on the force plate or pressure plate and executed a turn; when turning right, the left foot served as the stance (inside) foot and was analyzed, and vice versa for left turns.

All cohorts were given familiarization time before formal testing. In Groups A and B, familiarization consisted of several self-paced practice trials of walking, running, and turning until the participant understood the task and could contact the pressure plate cleanly. A formal treadmill warm-up was not used in these younger cohorts in order to avoid unnecessary fatigue and to preserve natural movement patterns during a relatively short plantar-pressure protocol. Testing for Groups A and B was therefore completed within a single session.

In Group C, the protocol involved higher-demand locomotor tasks together with motion-capture and force-platform measurements; therefore, walking, running, turning-walk, and turning-run trials were performed on separate days to reduce cumulative fatigue and to maintain data quality across conditions. Before formal testing, Group C completed a standardized warm-up consisting of 10 minutes of treadmill running at approximately 8 km/h followed by lower-limb stretching, together with several practice trials of each movement.

A minimum of three successful trials per task was recorded for each participant in Groups A and B. This number was selected to provide a representative participant-level mean while limiting fatigue and loss of concentration in younger children. In Group C, up to seven successful trials per task were collected because the higher-demand tasks and the joint-level motion analysis required additional acceptable trials to ensure stable time-series profiles and sufficient high-quality force-platform contacts. Trials in which a subject did not contact the force/pressure plate cleanly (e.g., stepping off the plate during the turn) were discarded and repeated. For all cohorts, the same protocol was applied consistently within each group, and participant-level data used for inferential analysis were based on the average of successful trials. The experimental tasks and the turning protocol are illustrated in Figure 2.2.1.

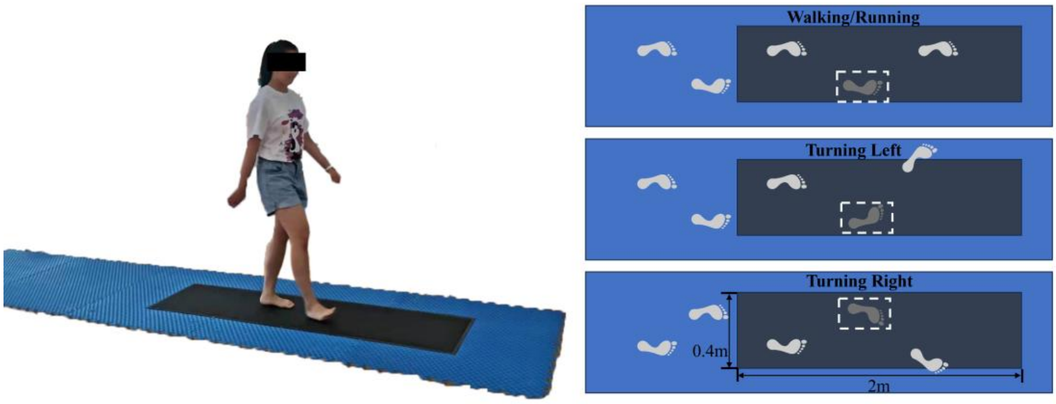


Figure 2.2.1 Illustration of the test protocol.

2.3 Data Acquisition

Plantar pressure data: Dynamic foot pressure during each trial was collected using an RsScan FootScan plantar pressure plate (RsScan International, Olen, Belgium) embedded flush in the middle of the walkway. The plate dimensions were 2.0 m × 0.4 m with a thickness of 0.02 m, containing 16,384 encapsulated sensors. The sampling frequency was set at 480 Hz. Prior to testing, the system was calibrated to each participant's body weight following established protocols. Participants were instructed to walk or run such that the foot of interest (as per task, e.g. left foot on a right turn) fully contacted the plate; the distribution of pressure across ten anatomical regions of the foot was recorded for each stance. The foot regions defined for analysis included the hallux (Toe 1), the lesser toes (Toes 2–5), the five metatarsal heads (M1–M5), the midfoot (MF), the medial heel (MH) and lateral heel (LH). These regions were delineated using the manufacturer's software (Figure 1C in original papers shows the regional map). All plantar pressure measurements were taken under identical barefoot conditions and by the same assessor using FootScan software to ensure consistency (Figure 2.3.1).

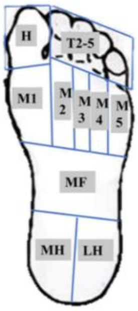


Figure 2.3.1 Plantar pressure acquisition.

Motion capture and force plate data: In Group C, three-dimensional kinematic data were recorded with an 8-camera Vicon motion capture system (Oxford Metrics, UK) at 200 Hz. A total of 39 reflective markers were placed on anatomical landmarks of the lower limbs and trunk according to a standard protocol (plug-in gait and additional markers for research purposes). Synchronized ground reaction force (GRF) data were collected at 1000 Hz from a Kistler force platform (Winterthur, Switzerland) embedded in the walkway. Kinematic and kinetic data streams were time-synchronized via the Vicon Nexus software during collection. Participants began each trial from a static standing posture on the force plate (feet parallel, arms crossed) so that a static trial could be recorded and then proceeded to perform the instructed movement (walk/run/turn) across the plate. The instant of initial foot contact was defined when the vertical GRF first exceeded 10 N, marking the start of stance phase [28]. All analog force data were zeroed and no filtering was applied in hardware beyond the system’s internal settings, as post-processing filters were applied subsequently.

2.4 Data Processing and Analysis

The process of data processing and analysis are showed in Figure 2.4.1. Plantar pressure metrics: For each trial, the stance phase was isolated from foot contact to toe-off using the force/pressure data. Time-series of the vertical plantar force (sum of all sensor outputs) and regional forces (for each of the 10-foot regions) were extracted for the stance phase [13]. To enable time-normalized comparisons, each raw force time-series was interpolated to a common length representing 0–100% of stance. Group A/B data were interpolated to 51–101 points (depending on study) using a cubic spline method [15,29], which provides a normalized temporal axis for averaging and statistical analysis. Center of pressure (COP) trajectories were computed for each stance by integrating the pressure distribution and determining the path of the resultant force. These COP paths (in the medio-lateral direction) were likewise normalized to % stance with a fixed number of points [30]. To quantify overall foot pronation/supination bias, the Foot Balance Index (FBI) was calculated from regional peak pressures [30]. Specifically, FBI is defined as the mean of the peak pressures under the metatarsal heads (M1–M5) minus the mean of the peak pressures under the heel (MH and LH) [30]. This index yields a measure of foot balance or arch pressure distribution: a positive FBI indicates a pronation tendency (greater forefoot pressure relative to heel), whereas a negative FBI indicates supination (relatively higher heel pressure) [30–31]. All plantar pressure processing was performed using the FootScan software and custom MATLAB scripts.

Kinematic and kinetic data: The 3D motion capture data were first post-processed in Vicon Nexus 1.8.6 to identify marker trajectories and GRF events [32]. The raw marker coordinates and force data were then exported in C3D format and imported into MATLAB R2019a for further analysis [20]. A global coordinate system was defined with the X-axis pointing forward (direction of walking progression), Y-axis vertical (upward), and Z-axis lateral (to the right) [33]. The marker trajectories were low-pass filtered at 6 Hz, and the force data were filtered at 30 Hz, using fourth-order zero-phase Butterworth filters to remove high-frequency noise while preserving signal shape [34]. Filtered kinematic and kinetic data were segmented to each stance phase (using the 10 N threshold for foot contact as noted) and time-normalized to 101 data points (0–100% stance) using a custom MATLAB script. This produced time-series curves for joint angles, joint angular velocities, joint moments, joint powers, and joint reaction forces for the ankle, knee, and hip of the stance limb over percentage of stance. In some analyses, these data were prepared for musculoskeletal modeling: the cleaned marker data and GRF were converted to .trc and .mot files respectively for input into OpenSim (Stanford University) to compute joint kinetics (moments, powers, etc.) via inverse dynamics.

Statistical analysis: To reduce trial-to-trial variability, multiple trials for each condition were averaged per participant prior to statistical comparisons. For Group A, three successful trials of each task were averaged; for Group C, seven trials were averaged – yielding one representative time-series per subject per condition. All data were checked for normal distribution (Shapiro–Wilk test) before inferential analysis. One-dimensional Statistical Parametric Mapping (SPM1d) was used to assess differences in the time-series data between conditions. Specifically, two-sample t-tests were conducted on the curves: for Group A and Group C, left vs. right foot comparisons were made; for Group B, SPD vs. healthy group comparisons were made for each foot or condition as appropriate. SPM analysis was implemented in MATLAB (using open-source SPM1d code) following Random Field Theory assumptions to account for the smoothness of time-series data. The SPM t-statistic continuum was evaluated against the critical threshold (based on $\alpha = 0.05$) to identify segments of the stance phase where the groups or sides differed significantly. Results were reported as significant $p<0.05$ intervals (%) of the stance phase. All statistical procedures for time-series were performed in MATLAB R2018a/R2019a with custom scripts and the spm1d package. In addition, for basic descriptive comparisons, mean ± standard deviation values of peak forces or indices were calculated for each condition. Because the SPD subgroup was relatively small ($n = 6$), the Group B analysis was interpreted as a tightly controlled cohort comparison rather than as a population-level estimate. Averaging multiple successful trials for each participant reduced within-subject variability before inferential testing; however, the limited subgroup size reduced statistical power, particularly for subtle effects and more variable turning conditions. Accordingly, Group B findings were interpreted with caution, with emphasis placed on the consistency, timing, and biomechanical coherence of the observed between-group differences across the stance phase.

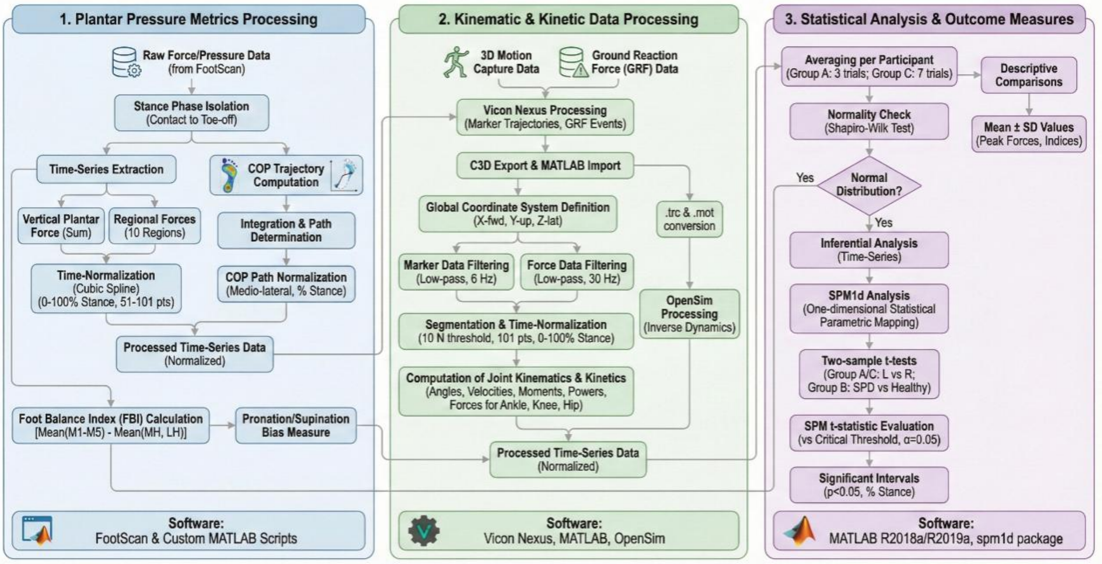


Figure 2.4.1 Flow diagram of data processing and analysis.

Note: (1) Planter pressure data processing by FootScan and MATLAB; (2) Kinematic and kinetic data processing by VICON, MATLAB, and OpenSim; (3) Statistical analysis and results output process conducted by SPM1D package in MATLAB.

3 Results

This chapter reports the findings in a task- and cohort-structured manner. Across all three cohorts, the main biomechanical message was that asymmetry was not absent in healthy participants, but its magnitude, direction, and timing depended strongly on task demand and measurement level. In Group A, asymmetry was modest in straight walking and became more evident in running and turning, especially in COP and selected forefoot variables. In Group B, SPD-related differences were minimal in walking but emerged most clearly in running, indicating task-dependent alterations in load transfer rather than a global disruption of gait. In Group C, joint-level asymmetry was widespread even in healthy adolescents and expanded further during turning, consistent with the unequal functional roles imposed by higher-demand locomotor tasks.

3.1 Center of Pressure Trajectory

In the young healthy cohort (Group A), clear lateral bias differences were observed between left and right feet in the COP trajectory during straight gait (Figure 3.1.1). As the children walked, the left foot's COP path tended to shift medially (indicating a pronation bias) while the right foot's COP remained relatively more lateral (supination bias), with the disparity between feet evident throughout most of the stance phase. A similar pattern was found during running: the left foot COP tracked more medially and the right more laterally, and a statistical comparison confirmed significant differences in COP position between left vs. right across the entire stance phase in both walking and running ($p<0.001$).

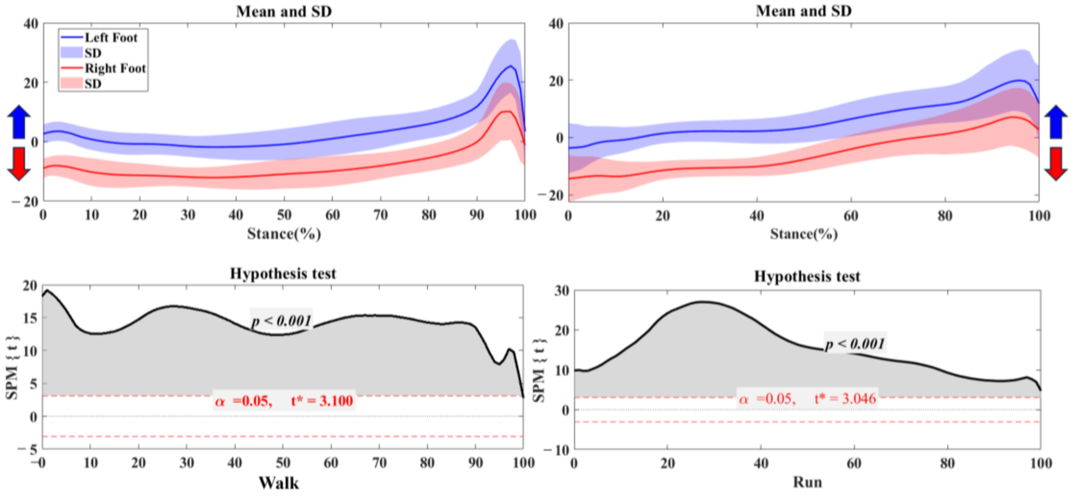


Figure 3.1.1 The COP of trajectory in the left and right foot during walking and running with the highlighted direction of pronation (Blue arrow) and supination (Red arrow).

Note: Y-axis (%foot width).

During turning tasks, the COP behavior depended on turn direction (Figure 3.1.2). For turns to the left, the stance (left) foot's COP trajectory shifted further medially (toward pronation), whereas for right turns, the stance (right) foot's COP shifted laterally (toward supination). These opposite COP deviations led to significant differences in COP trajectories when comparing left-turn vs. right-turn stances over substantial portions of the stance phase ($p<0.001$ in both walking and running turns).

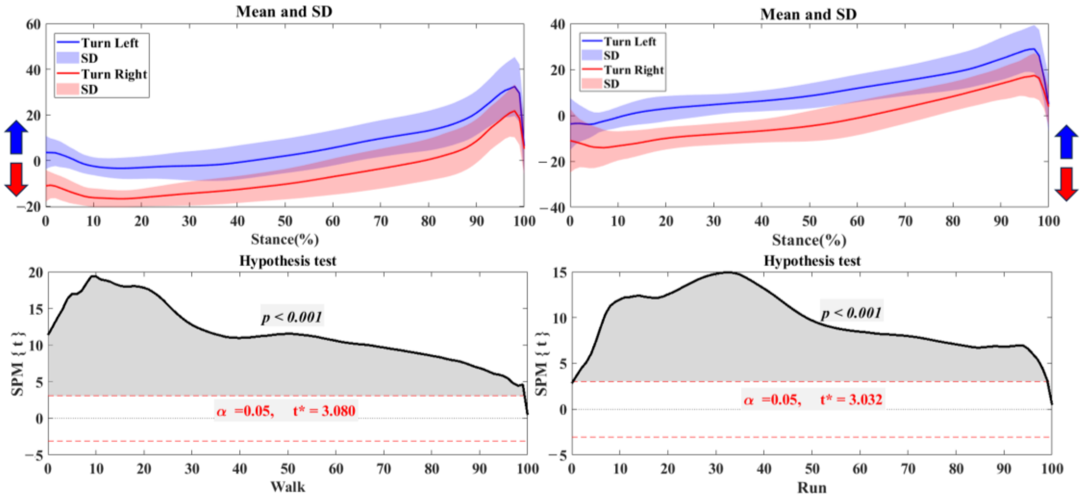


Figure 3.1.2 The COP of trajectory in the turning right/left during walking and running with the highlighted direction of pronation (Blue arrow) and supination (Red arrow).

Note: Y-axis (%foot width).

In the SPD vs. healthy children (Group B), overall COP patterns were qualitatively similar between groups, but subtle differences emerged near toe-off (Figure 3.1.3). During straight walking and running, both groups exhibited a lateral COP roll-off on the right foot and a more medial COP path on the left foot (i.e., both groups showed the pronation/supination laterality noted above). No significant between-group difference was found in COP trajectory for the left foot; however, in the right foot COP an angular deviation appeared in the healthy controls at the end of stance that was less pronounced in SPD children. Specifically, during the push-off phase (~90–100% of stance) of the right foot, healthy children's COP moved slightly more medially (indicating greater pronation) compared to SPD peers, yielding a significant group difference in that late stance interval ($p < 0.05$).

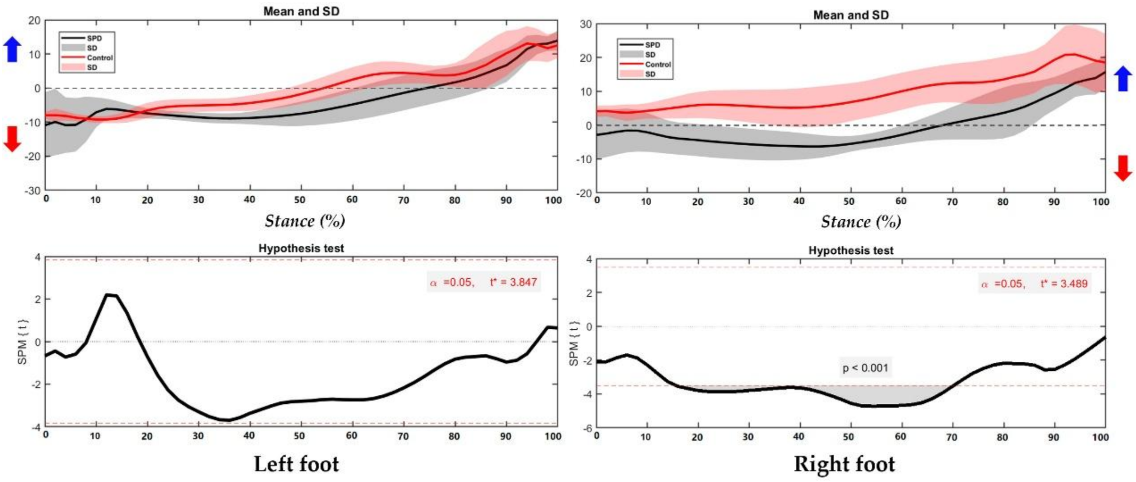


Figure 3.1.3 The COP of trajectory in the left foot and right foot during running with highlighted direction of pronation (Blue arrow) and supination (Red arrow).

In turning gait, group differences were more noticeable in the right (inside) foot during turns (Figure 3.1.4). For a rightward turn (where the left foot is stance), both SPD and control children’s left-foot COP went into pronation with no significant difference between groups. But for a leftward turn (right foot stance), the healthy controls showed a markedly more pronated COP path through mid-stance compared to SPD children. Statistically, the right-foot COP in left turns differed significantly between healthy vs. SPD over approximately 16%–69% of the stance phase (p<0.001), whereas the left-foot COP in right turns remained similar between groups.

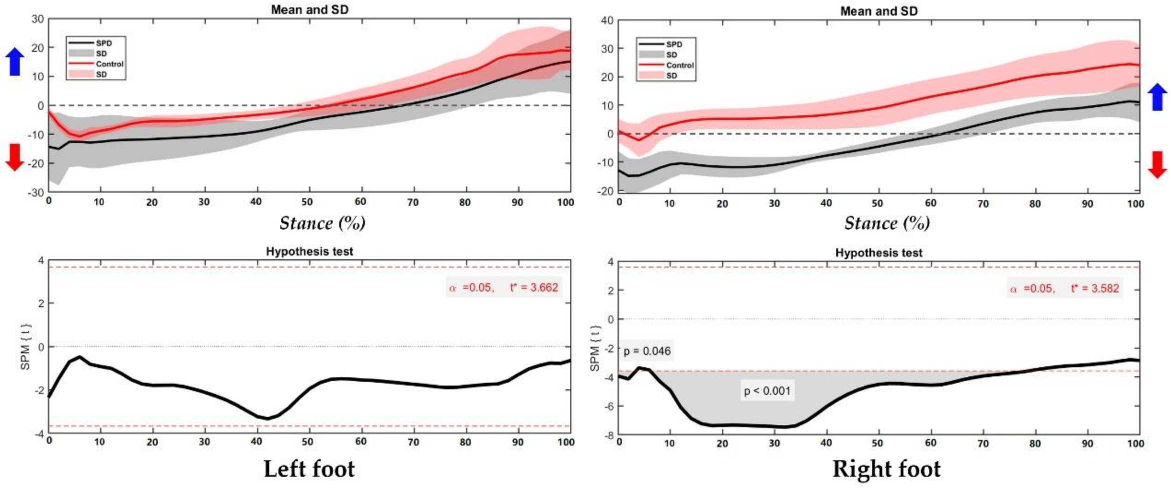


Figure 3.1.4 The COP of trajectory in the left foot and right foot during right/left turning with highlighted direction of pronation (blue arrow) and supination (red arrow).

3.2 Foot Balance Index

Among typically developing children (Group A), the Foot Balance Index (FBI) values reflected a lateral asymmetry consistent with the COP findings. On average, the left foot exhibited negative FBI values, indicating a tendency toward pronation (higher forefoot pressure relative to heel), whereas the right foot showed positive FBI values, indicating a relative supination tendency. This left-vs-right difference in FBI was modest during walking but became more pronounced during running. In the running condition, the divergence between left and right FBI reached significance over roughly the middle half of stance: the FBI curve for the left foot was significantly lower (more negative) than the right foot's curve between ~18% and 53% of the stance phase ($p<0.001$). This indicates that during running mid-stance, the left foot was in a markedly more pronated state compared to the right (Figure 3.2.1).

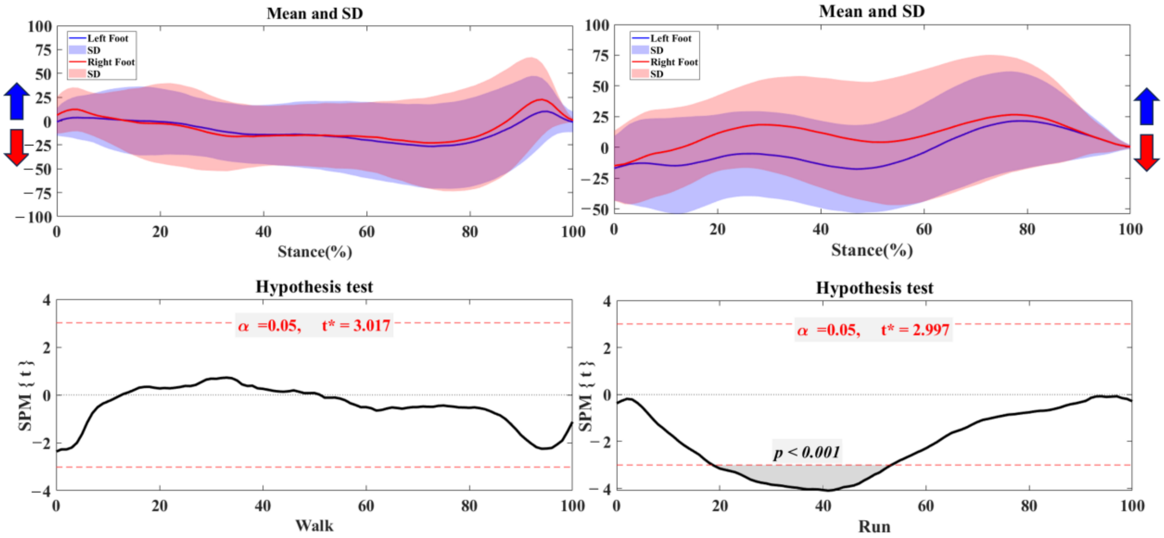


Figure 3.2.1 The FBI of trajectory in the left and right foot during walking and running with the highlighted direction of pronation (Blue arrow) and supination (Red arrow).

Note: Y-axis (%).

During the turning tasks, FBI trajectories for both feet followed the direction of the turn: in left turns (right foot stance) the index shifted negative (pronation bias) and in right turns (left foot stance) the index shifted positive (supination bias). These shifts were more extreme in running turns than walking turns, although when comparing turning left vs. right, the differences in FBI did not reach statistical significance in either condition (no significant effect of turn direction on FBI asymmetry). Overall, Group A's results suggest a consistent intrinsic asymmetry – the left foot relatively pronated and right foot relatively supinated – especially under higher dynamic loads like running (Figure 3.2.2).

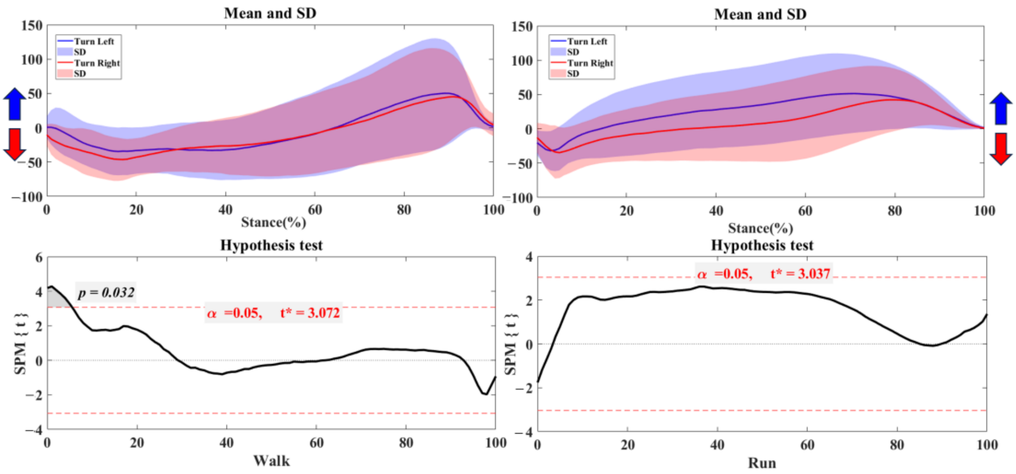


Figure 3.2.2 The FBI of trajectory in the turning right/left during walking and running with the highlighted direction of pronation (Blue arrow) and supination (Red arrow).

Note: Y-axis (%).

For Group B, the comparison of FBI between SPD children and healthy controls revealed no significant overall difference in foot balance when averaged across the stance. Both groups had similar FBI profiles for left and right feet during basic walking and running, indicating that the presence of sensory processing disorder did not grossly alter the distribution of pressure between forefoot and heel during gait. However, subtle group differences emerged at specific phases of gait. Notably, in the running task, healthy children demonstrated a sharper increase in FBI (toward pronation) at the end of stance (push-off) in the right foot, whereas SPD children maintained a more limited range of FBI change. This led to a statistically significant group difference in the right foot FBI during ~47–63% of the stance phase, corresponding to mid to late stance (p<0.001). Essentially, the healthy group's right foot rolled inward (pronated) more during mid/late stance than the SPD groups (Figure 3.2.3).

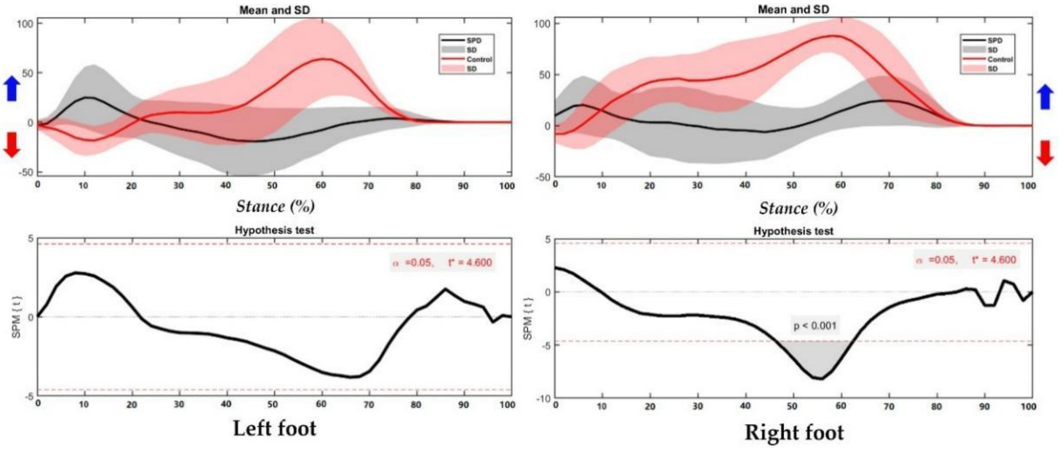
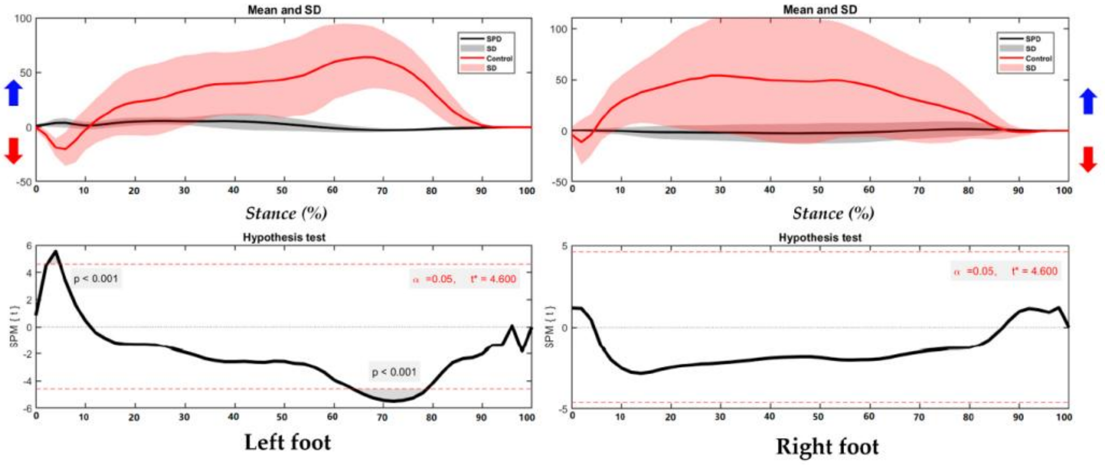


Figure 3.2.3 FBI in the left foot and right foot during running with highlighted directions of pronation (blue arrow) and supination (red arrow).

During turning movements, both groups showed larger oscillations in FBI due to the more complex loading patterns. Healthy children exhibited noticeable supination–pronation shifts in FBI for both feet when turning (indicating a responsive medial-lateral weight transfer), whereas SPD children's FBI curves were comparatively flatter, suggesting restricted foot inversion/eversion adjustments. In left-turn trials (right foot stance), for example, healthy kids displayed an initial supination then pronation toward push-off, whereas SPD kids showed a blunted response. Some of these differences approached significance: e.g., at the very start of stance and at push-off in the left foot FBI during turning, SPD vs. control differences were observed (with p slightly < 0.05 in isolated intervals). Overall, while FBI magnitudes were similar between groups, healthy children tended to use a greater range of foot motion (from supinated to pronated positions) especially in dynamic tasks, compared to children with SPD (Figure 3.2.4).



Left foot **Right foot**

Figure 3.2.4 FBI in the left foot and right foot during turning with highlighted direction of pronation (blue arrow) and supination (red arrow).

3.3 Plantar Pressure Distribution and Ground Reaction Forces

Firstly, Group A (healthy children), the plantar pressure analysis revealed several significant left-to-right asymmetries concentrated in specific regions of the foot and specific phases of stance (Figure 3.3.1). During straight walking, the only notable asymmetry occurred in the lateral forefoot. The peak pressure under the second metatarsal (M2) region was significantly lower in the left foot compared to the right foot toward the end of stance (approximately 76%–95% of the contact phase, p<0.01). No other foot region showed a significant bilateral difference in walking.

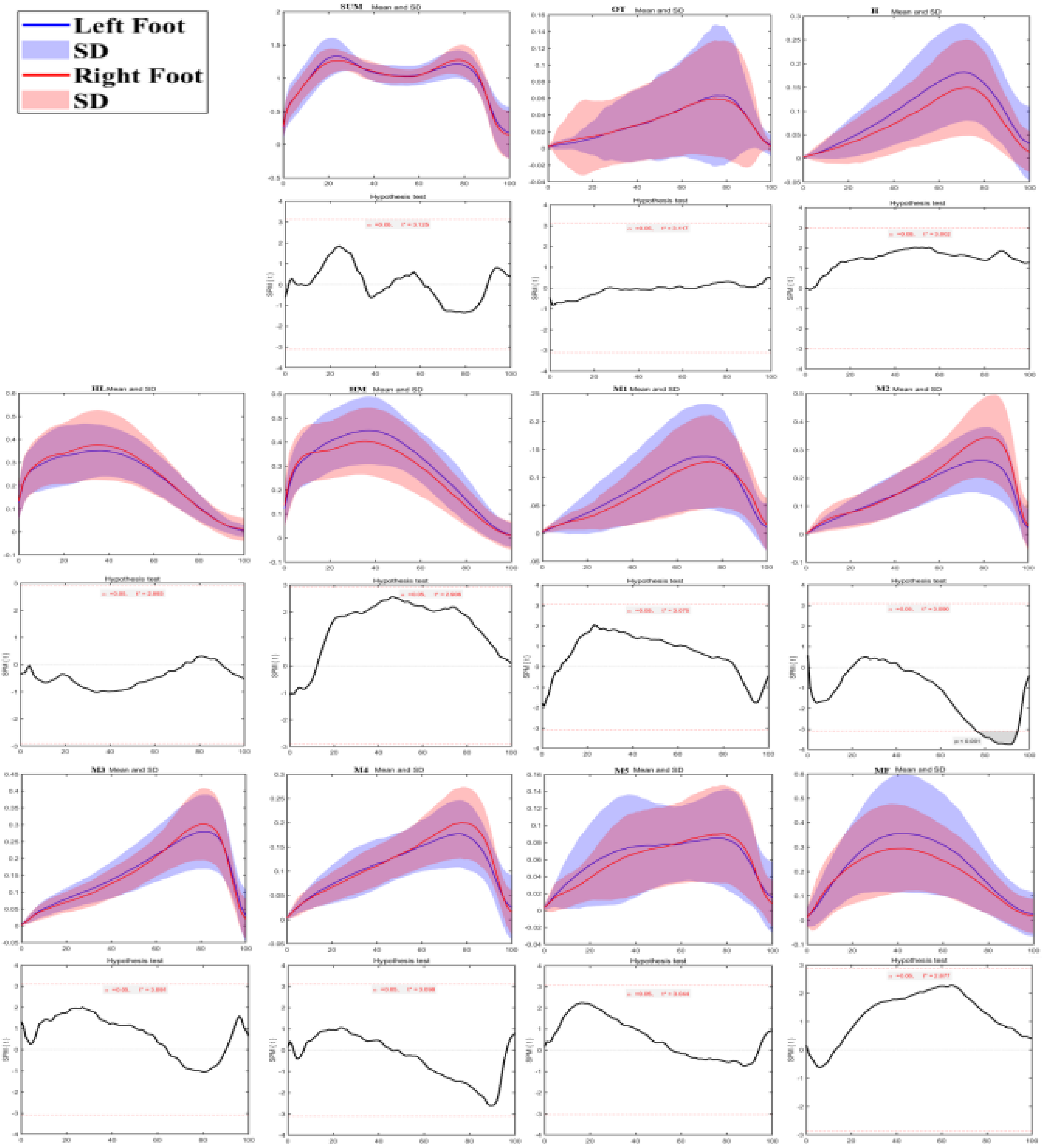


Figure 3.3.1 The sum of plantar pressure (SUM) and regional plantar forces during walking on the left foot and right foot with highlighted statistics.

In running, more pronounced asymmetries emerged, the left foot bore significantly less pressure in the medial forefoot but more in the lateral forefoot relative to the right foot (Figure 3.3.2). In the left foot's M1 region (first metatarsal head), pressures were lower than the right foot during early stance (~10%–54%, $p<0.01$). Conversely, the left foot's M4 region (lateral forefoot) showed higher pressure than the right between ~16% and 35% of stance ($p<0.01$), and the M5 (5th metatarsal) region of the left foot had higher pressure from ~5% up to 78% of stance ($p<0.01$). These findings indicate that in running, the right foot concentrated more load under the medial forefoot (toe-off likely biased medially), whereas the left foot experienced more loading on the lateral forefoot. No significant differences were seen at the heel regions in running.

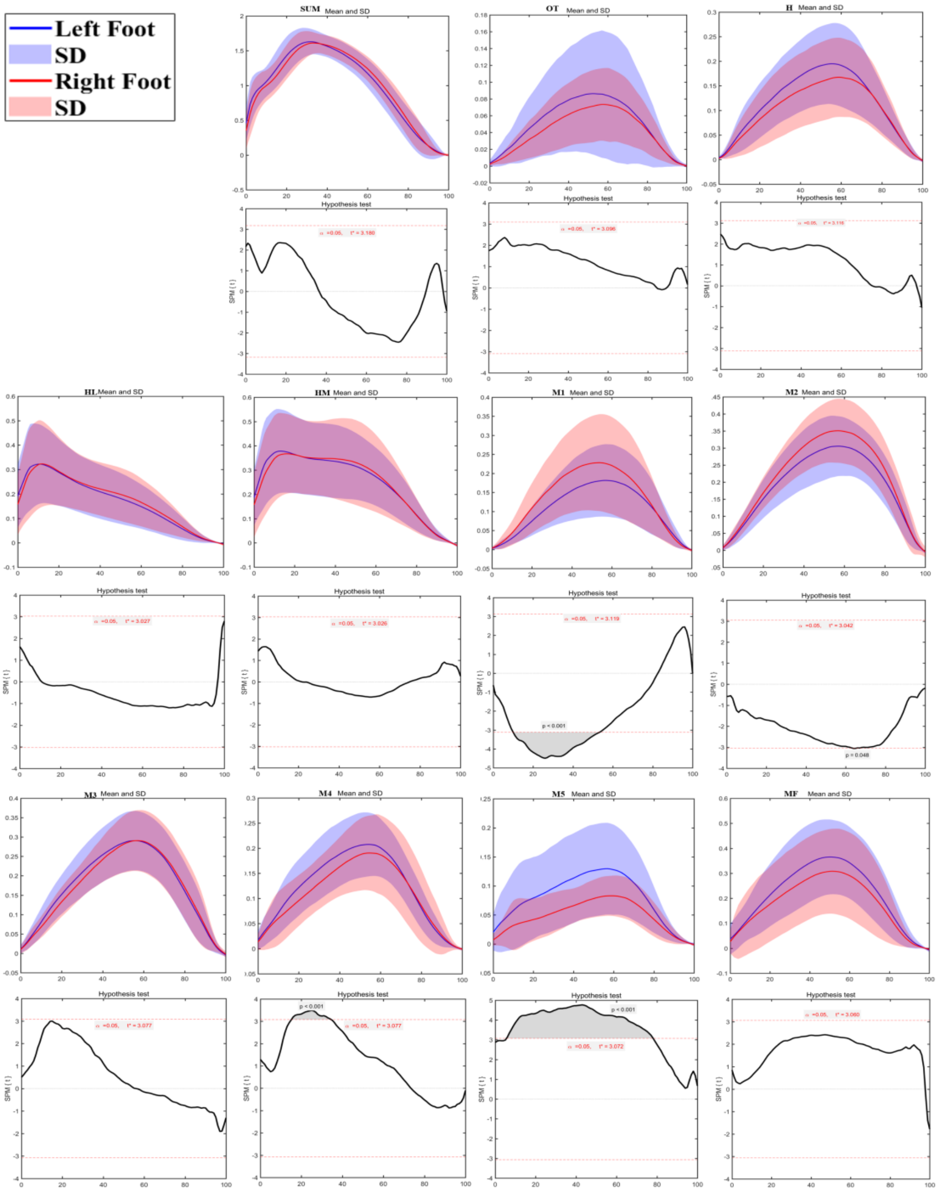


Figure 3.3.2 The sum of plantar pressure (SUM) and regional plantar forces during running in the left foot and right foot with highlighted statistics.

During turning while walking, bilateral differences depended on turn direction (Figure 3.3.3). When comparing left-turn vs. right-turn stances, the heel (H) region in left turns (i.e., left foot stance during a rightward turn) had significantly lower pressure than in right turns at several brief periods: at ~3–4% and 8–9% of stance (early loading response) and again at 25%–38% of stance (mid-stance), with p ranging from 0.05 down to <0.01. This suggests that when the children turned right (using left foot as pivot), the left heel was unloaded faster or more completely than the right heel would be during a left turn. Later in the stance phase of turning-walk, the M2 region in left-turn trials showed higher pressure than in right-turn trials (significant from ~76%–92% of stance, p<0.01), indicating the left forefoot bore more late-stance load in a rightward turn. No other region differed significantly between turning directions in walking.

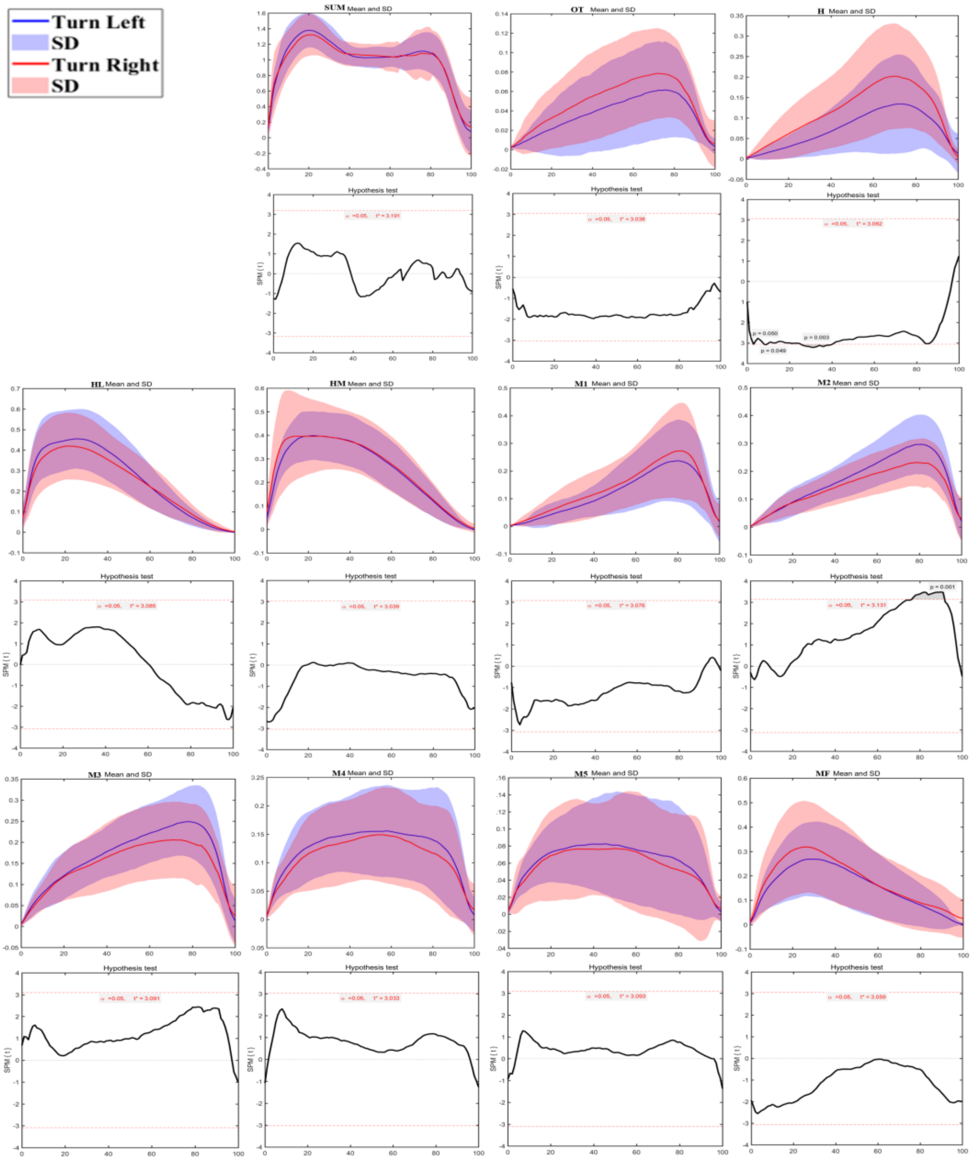


Figure 3.3.3 The sum of plantar pressure (SUM) and regional plantar forces during Turning Walking Tasks in the left turn and right turn with highlighted statistics.

In turning while running, a complex pattern of asymmetry was observed as the children executed cutting maneuvers at speed (Figure 3.3.4). Overall, the left foot (stance foot in a rightward cut) tended to experience greater forefoot loading than the right foot (stance in a leftward cut) in several areas, but also less in others. For instance, during a rightward cut, the left foot's M1 pressure was higher than the right foot's (left turn) during 9%–16% of stance (p=0.032), and left M4 and M5 regions carried significantly greater pressure in mid-to-late stance (M4: 46%–76%, p<0.01; M5: 39%–88%, p<0.01). On the other hand, the left foot's M3 region had lower pressure than the right foot's during the first ~9% of stance (p=0.025), and left M4 was also lower very early (1%–5%, p=0.043). In summary, for turning runs the bilateral differences were dispersed: the left foot (when it was the inside foot on a turn) showed some advantages in pressure in certain lateral regions but disadvantages in others, reflecting how weight shift and pivoting differed between turning directions. Importantly, aside from the regions noted, no other plantar regions showed significant bilateral differences in any task, suggesting that asymmetries were localized rather than global.

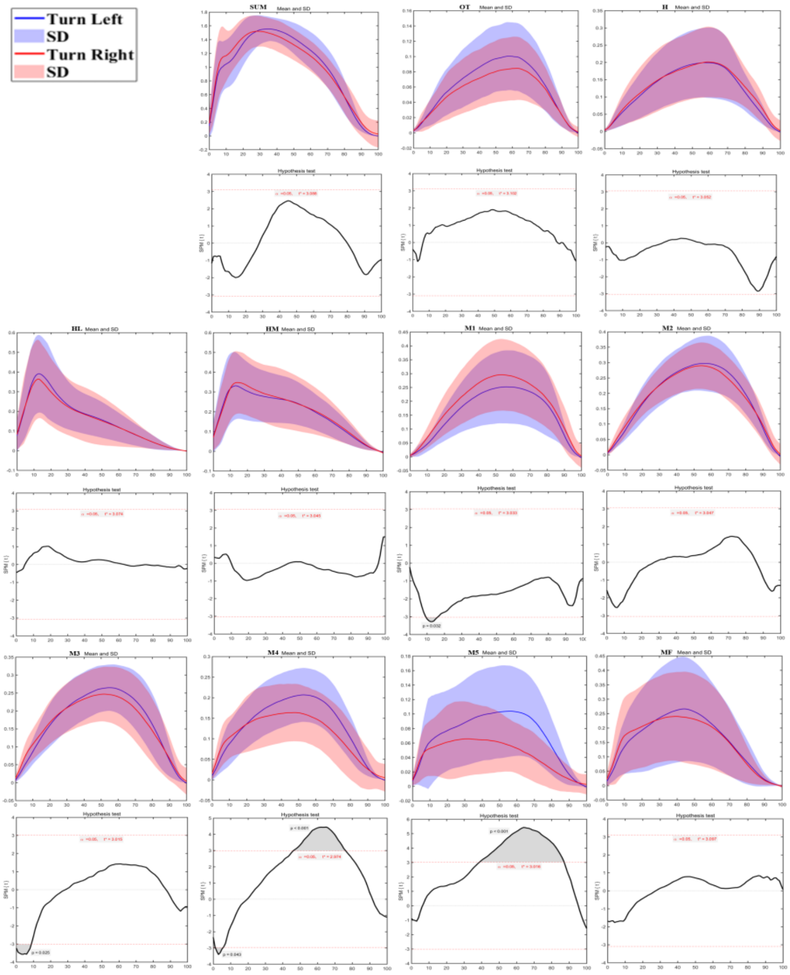


Figure 3.3.4 The sum of plantar pressure (SUM) and regional plantar forces during Turning running Tasks in the left turn and right turn with highlighted statistics.

When it comes to Group B (SPD vs. control), the overall magnitudes and patterns of plantar loading were similar between SPD children and typically-developing controls during straightforward gait, but differences arose under more dynamic conditions (Figure 3.3.5). In level walking, the two groups did not show any significant differences in either the total plantar force (vertical GRF) profiles or the regional pressure distributions under any part of the foot. Both SPD and healthy children had comparable pressure-time curves for all foot regions during walking, indicating symmetric walking performance for gross pressure metrics.

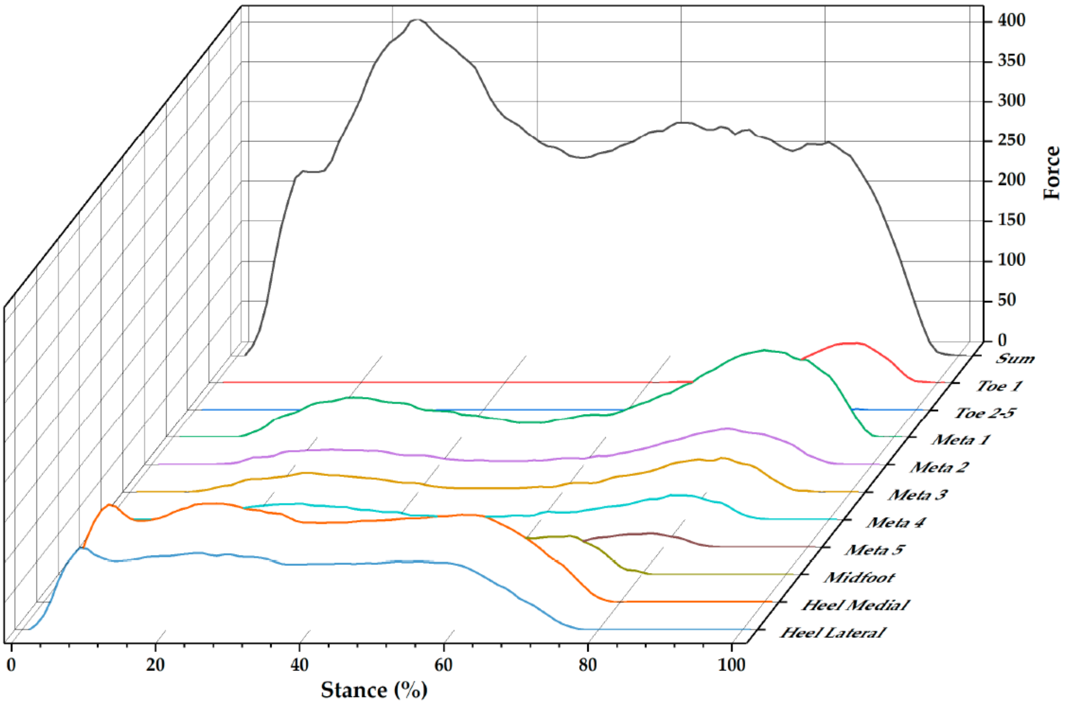


Figure 3.3.5 Example of regional and sum ground reaction forces during walking.

In running (Figure 3.3.6), however, the typically developing children generated higher forces than the SPD group. The peak vertical GRF was greater in the healthy controls, especially noticeable in the left foot: throughout approximately 22%–63% of the stance phase, the left-foot GRF of healthy children was significantly higher than that of SPD children ($p<0.001$). The right foot showed a similar trend of higher GRF in healthy kids during running, though those differences did not reach significance. Correspondingly, the regional plantar pressures during running differed between groups in multiple areas. Healthy children exerted significantly larger pressures in the forefoot and toe regions compared to SPD peers. For the left foot in running, healthy controls had greater forces under the hallux (Toe 1) for 7%–62% of stance and under the lesser toes (T2–5) at the very end of stance (98%–100%). They also showed higher pressure in the medial forefoot: M1 (at 1%–4% of stance), M2 (33%–69%), M3 (14%–62%), and even in the medial heel (56%–83% of stance) – all these intervals had $p<0.05$ to <0.001 favoring higher pressures in healthy children. In contrast, SPD children exhibited one region with consistently higher pressure: the midfoot. The left midfoot region in SPD children sustained significantly greater pressure than in healthy children for 29%–57% of the stance ($p<0.001$). A similar pattern was observed in the right foot during running: healthy children loaded Toe 1 (significantly higher force from 8%–26% stance) and showed brief higher loading of toes 2–5 (19%–22%) and M1 (23%–26% and 63%–72%) and the lateral heel (14%–24%) compared to SPD children. Meanwhile, SPD children's right midfoot bore much more force than that of healthy children through almost the entire stance (approximately 6%–100%, $p<0.001$). These results suggest that SPD children, when running, rely more on midfoot loading (flatter foot placement), whereas healthy children concentrate forces more at the toes and metatarsals (perhaps indicating a more effective push-off).

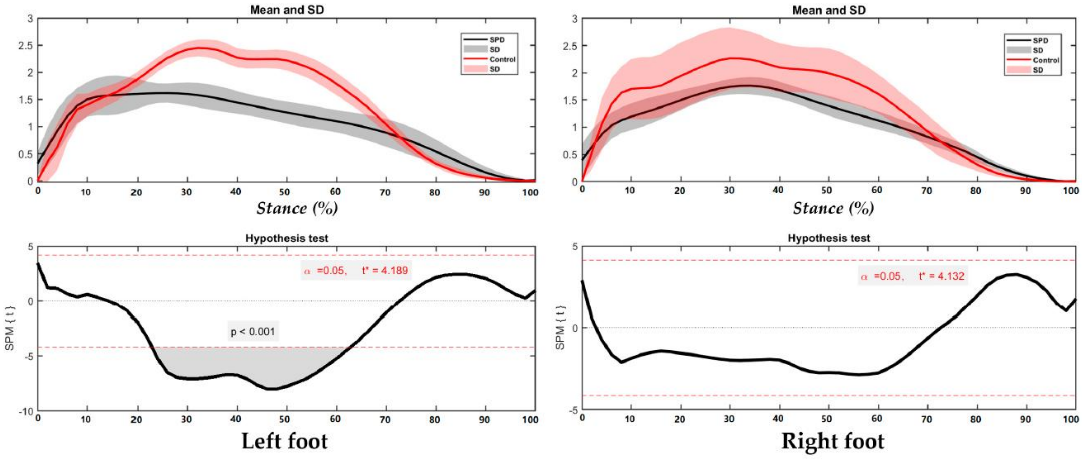


Figure 3.3.6 The vertical ground reaction force (GRF) in the left foot and right foot during running in SPD children and healthy controls

In turning gait, group differences in GRF inverted in some aspects compared to straight running (Figure 3.3.7). During cutting maneuvers, the SPD children in certain instances produced equal or even greater foot forces than controls, especially at specific moments of stance. For example, in a rightward cut (left foot is inside), the left foot of SPD children showed higher instantaneous GRF than healthy children at initial contact (~1%–2% of stance) and again during early mid-stance (~11%–15%), although these spikes were relatively brief. The healthy children, on the other hand, tended to have higher force toward mid/late stance of the turn: the right foot GRF of healthy kids (during a leftward cut) was higher around 35%–52% of stance and after, but those differences were not statistically significant. In general, neither group showed a clear consistent advantage in total force during turning – the demands of the maneuver led to variability.

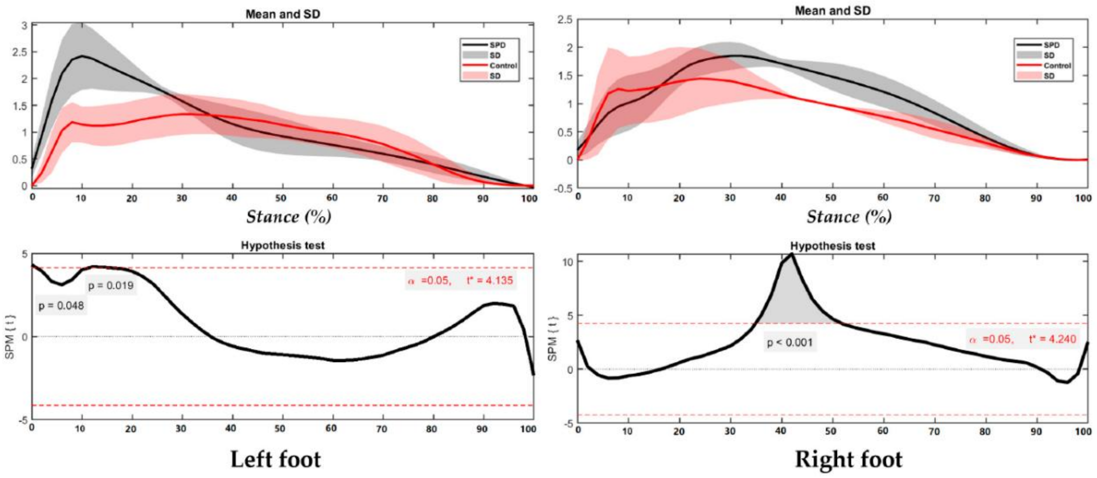


Figure 3.3.7 The vertical ground reaction force (GRF) in the left foot and right foot during turning in the SPD children and healthy controls.

The regional pressure outcomes in turning were complex; many did not reach significance and detailed results were provided in supplemental figures in the original study. Qualitatively, healthy children appeared to utilize their toes and medial forefoot more during cutting (consistent with their straight-run pattern), whereas SPD children had a more cautious loading pattern with relatively greater midfoot reliance and less extreme medial-lateral shifts. For instance, during turns the healthy group’s forefoot (toes, M1–M3) sometimes showed higher peaks than SPD, while SPD could show slightly more even distribution. However, these differences were less systematic than in straight running and often did not attain statistical significance for prolonged periods. In summary, Group B results indicate that under the high-demand condition of running, children with SPD exhibit altered load distribution (less forefoot push-off pressure, more midfoot load) compared to peers, whereas in low-demand walking their plantar pressure patterns are essentially normal (Figure 3.3.8 and Figure 3.3.9).

Taken together, the SPD–control comparison revealed a clearly task-dependent profile rather than a global gait abnormality. No statistically significant between-group differences were detected during level walking, whereas the strongest and most consistent differences emerged during straight running. These running-related effects were most evident in variables describing load transfer and foot rollover: compared with controls, children with SPD showed lower distal loading, reduced right-foot COP/FBI modulation, lower left-foot GRF, and markedly greater midfoot loading—particularly in the right foot, where the difference persisted across almost the entire stance phase. By contrast, turning-related differences were present but less uniform, being most apparent in the right/inside-foot COP during left turns and otherwise limited to brief or isolated intervals. Overall, the SPD findings were predominantly phase-specific rather than global, with the clearest exception being the near whole-stance right-midfoot loading difference during running, indicating that SPD was associated mainly with task-dependent alterations in load transfer rather than a generalized disturbance of gait mechanics.

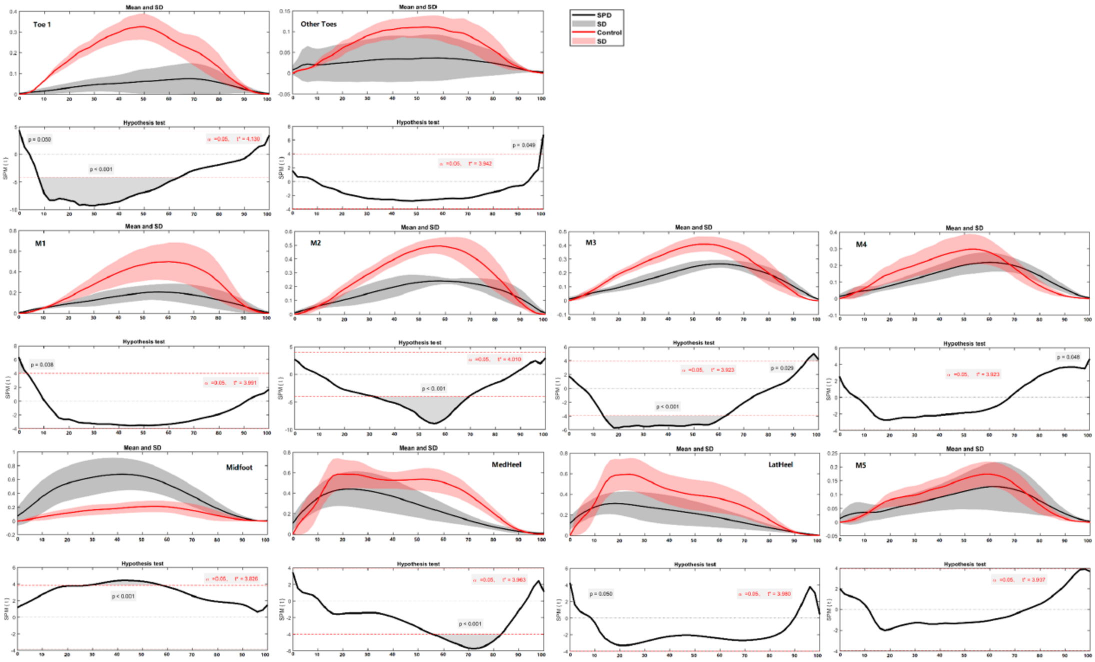


Figure 3.3.8 The regional plantar forces in the left foot during running in the SPD children and healthy controls with highlighted statistics.

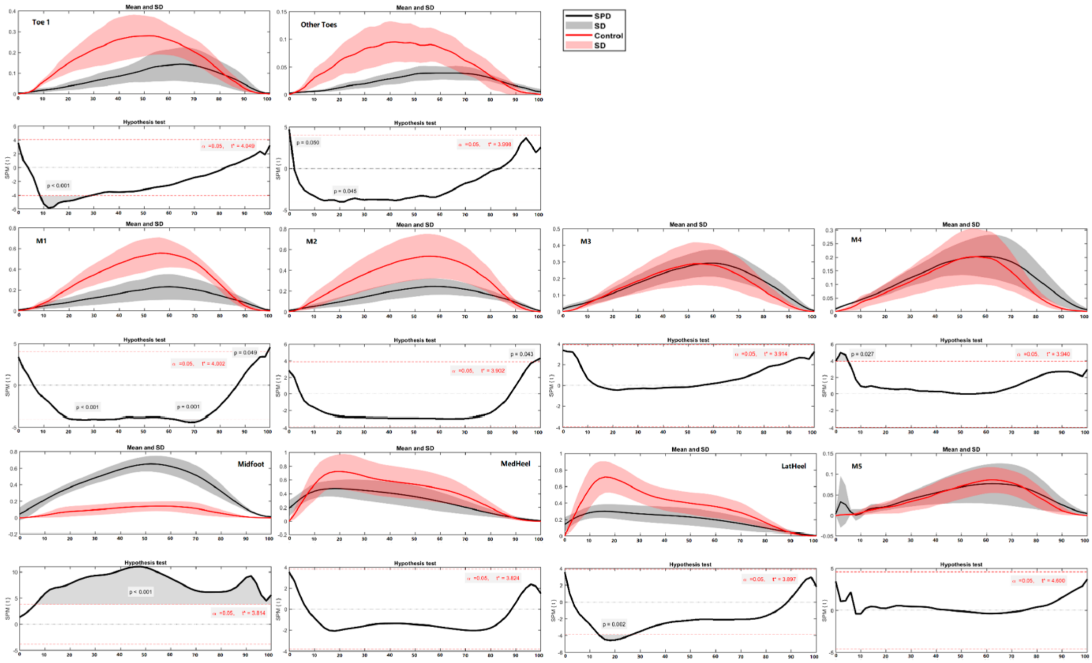


Figure 3.3.9 The regional plantar forces in the right foot during running in the SPD children and healthy controls with highlighted statistics.

During aggressive turning, both groups experience challenging load shifts and only subtle differences emerge (e.g., timing of weight transfer), suggesting that dynamic stability in cuts may be somewhat reduced in SPD children but not grossly abnormal (Figure 3.3.10 and Figure 3.3.11).

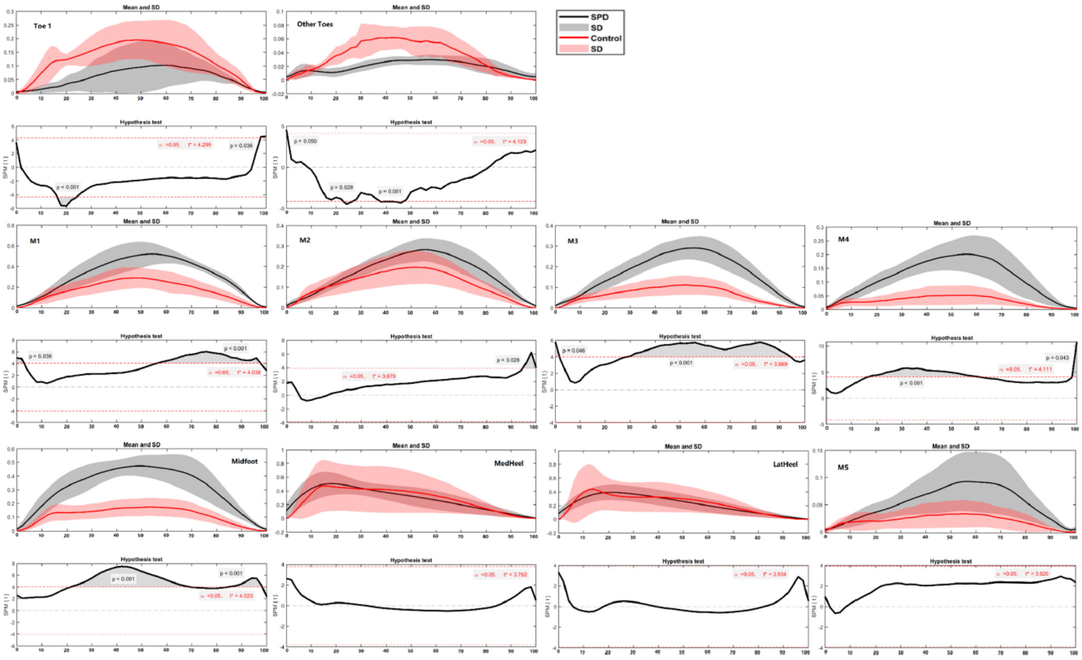


Figure 3.3.10 The regional plantar forces in the left foot during turning in the SPD children and healthy controls with highlighted statistics.

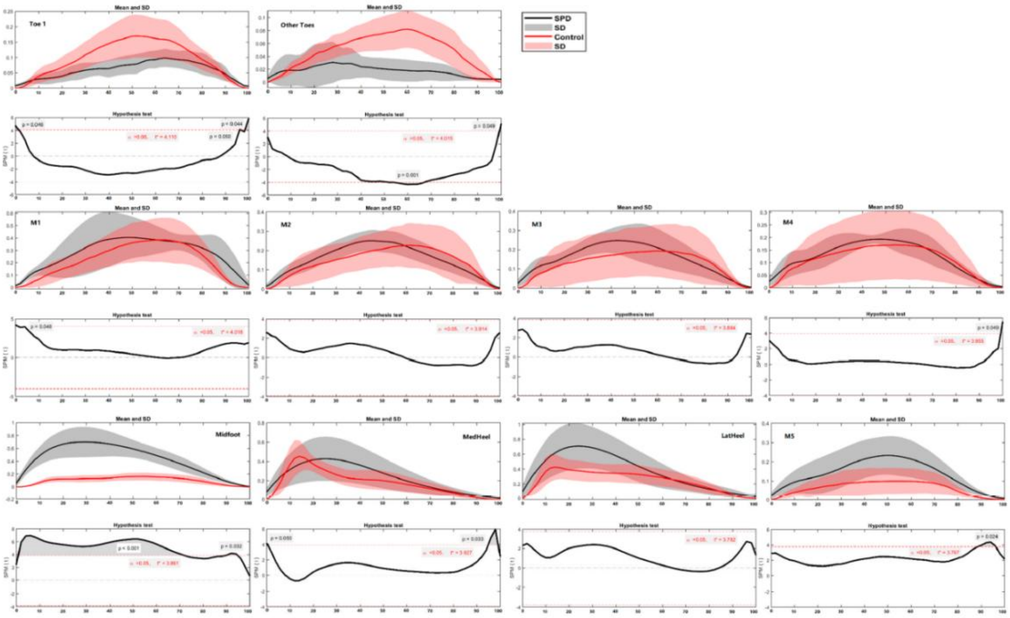


Figure 3.3.11 The regional plantar forces in the right foot during turning in the SPD children and healthy controls with highlighted statistics.

3.4 Lower-Limb Kinematics and Kinetics

The Table 3.4.1, Table 3.4.2 and Table 3.4.3 are the summary tables highlighting variable, task, direction of asymmetry, and stance phase.

For the adolescent athletes (Group C), significant bilateral asymmetries were found in nearly all examined joint kinematic and kinetic variables during the stance phase of gait. These asymmetries were present in each task (walking, running, and their turning equivalents), though the magnitude and duration of differences varied by task. In running, the left vs. right differences were especially pronounced. Throughout the stance phase of running, the dominant (right) limb tended to exhibit greater ranges or magnitudes in joint motion and force compared to the non-dominant (left) limb (Figure 3.4.1). For example, the right ankle joint angle remained significantly more dorsiflexed/plantarflexed (difference in angle) than the left ankle for 0–71% and again 85–100% of the stance phase ($p<0.001$ in early stance; $p<0.026$ in late stance). The right knee angle was also significantly different (more extended) than the left from 0–24% of stance ($p<0.017$). The right hip angle differed from the left over the entire stance (0–100%, $p<0.001$), indicating a consistently different hip posture (e.g., perhaps more extended or adducted) on the right side. Similarly, joint angular velocities showed large asymmetric intervals: the angular velocity of the right ankle was significantly higher than left during 5–75% and 79–100% of stance ($p<0.001$ and $p=0.002$ in late stance), and the right knee had higher angular velocity than left from 0–61% and 68–100% ($p<0.001$ for much of stance). Right hip angular velocity exceeded left mainly in mid-stance (36–61%, $p<0.001$). These differences suggest, for instance, a faster extension or rotation of one limb versus the other during stance. In terms of joint moments, the analysis revealed that the right limb generated greater internal moments at certain joints over substantial portions of stance: e.g., the ankle plantar-flexor moment was higher on the right from 18–61% of stance ($p<0.001$), the knee extensor moment from 0–16% and 77–89% ($p<0.01$), and the hip extensor moment from 65–91% ($p<0.001$). The joint power (mechanical power output/absorption) also differed, with the right ankle showing higher power than left during 3–13% and 45–76% of stance ($p<0.01$), the right knee higher at 0–17%, 66–75%, 94–100% ($p<0.01$), and the right hip higher at multiple periods (0–7%, 18–55%, 64–97%; p from <0.01 to <0.001). Even the joint reaction forces (reflecting dynamic loading at the joints) were asymmetric: the right ankle joint force was greater than left during 20–37% of stance ($p<0.01$), right knee force higher at 17–61% ($p=0.001$), and right hip joint force higher for almost the entire stance (0–72% and 75–100%, $p<0.01$). Collectively, these running results demonstrate that one limb (in this case the right, dominant leg) was consistently experiencing different kinematic patterns and higher kinetic loading in various phases of stance compared to the other limb, pointing to functional asymmetry even in healthy young athletes.

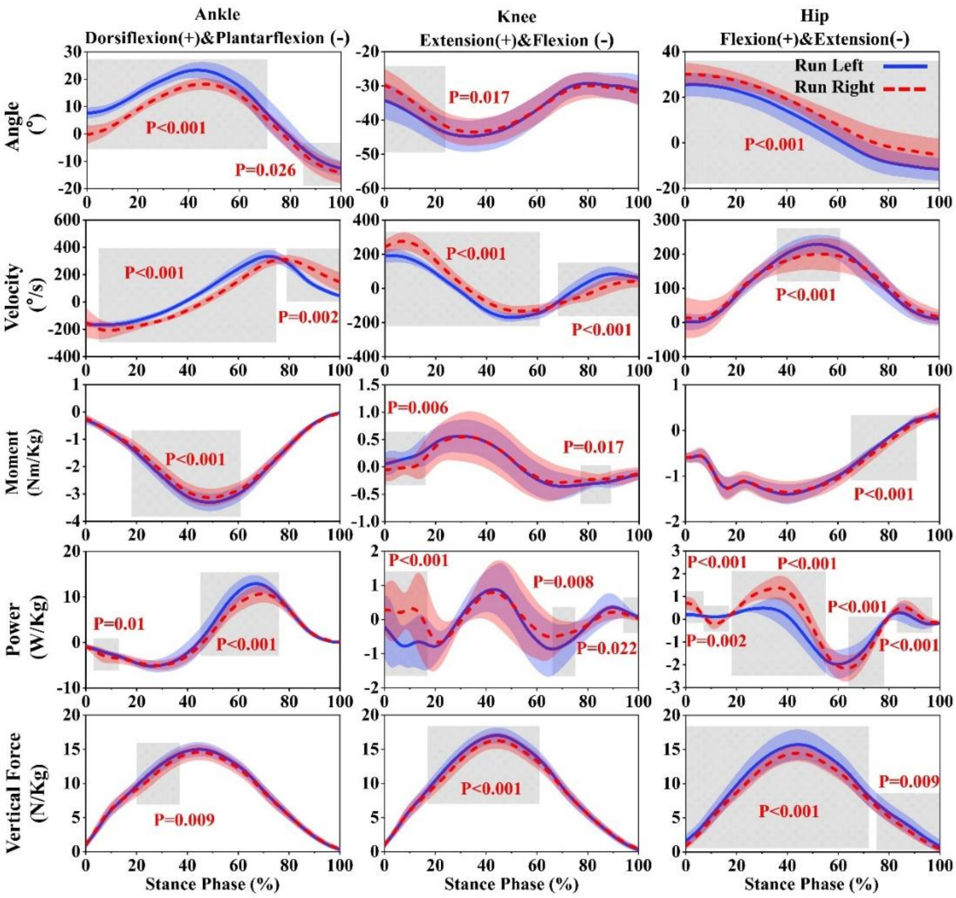


Figure 3.4.1 Illustration of the results between the left and right lower limb showing the statistical parametric mapping outputs for the angle, velocity, moment, power and force of the ankle, knee, and hip during the running stance phase. Grey shades represent the significant differences and t-values of the statistical parametric mapping (SPM) for all participants (post hoc results).

During the turning while running task, asymmetries between limbs were also extensive. In a cutting maneuver, the demands on the inside vs. outside leg differ, and the analysis confirmed significant differences for the inside (e.g., left) vs. outside (right) leg (Figure 3.4.2). The right (outside) ankle angle was significantly different from the left for nearly the entire stance (approximately 18%–100%, $p<0.001$), and the right knee angle for the latter half of stance (42%–100%, $p<0.001$). Ankle and knee angular velocities were likewise asymmetric through large portions of the stance (e.g., ankle velocity differed 69%–100%, knee 0–48% and 68%–100%, $p<0.001$). Joint moment asymmetries in the turn were pronounced: the ankle moment differed from 3%–84% of stance ($p<0.001$), knee moment 0%–75% and 82%–100% ($p<0.001$), and hip moment had multiple intervals of difference (e.g., 0–11%, 18%–30%, 61%–100%; p ranging <0.005 to <0.001). Power output of ankle, knee, and hip in turning also showed bilateral disparities over the majority of stance (ankle power differed 0–42% and 64%–86%; knee 0–30%, 33%–73%, 79%–100%; hip 17%–58% of stance; all $p<0.001$). These results reflect the unequal functional roles of the inner vs. outer limb when cutting: one limb (often the outside leg) may bear greater deceleration or turning force, leading to higher moments and power absorption, whereas the other provides propulsion – leading to measurable kinematic and kinetic differences.

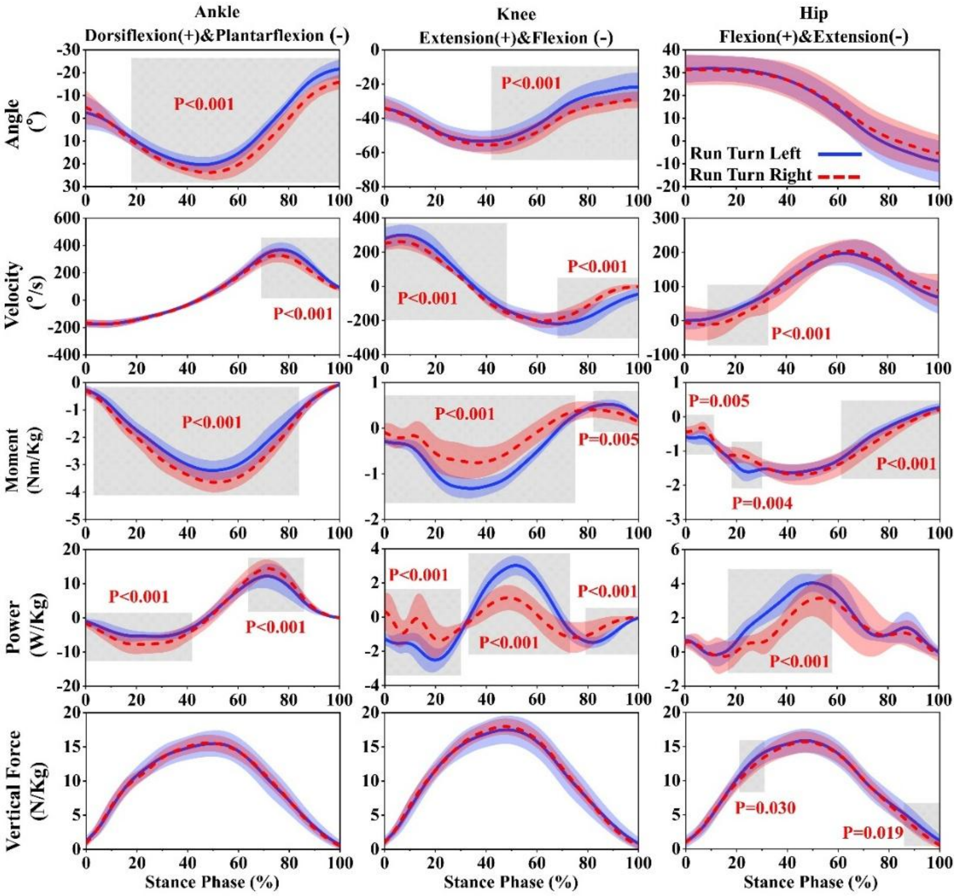


Figure 3.4.2 Illustration of the results between the left and right lower limb showing the statistical parametric mapping outputs for the angle, velocity, moment, power and force of the ankle, knee, and hip during the turning while running stance phase. Grey shades represent the significant differences and t-values of the statistical parametric mapping (SPM) for all participants (post hoc results; dashed red lines represent the results at $p = 0.05$).

In the walking task, asymmetries were present but generally over shorter portions of stance than in running (Figure 3.4.3). Still, significant differences were found. The right ankle angle was greater than left from 0–74% of the walking stance ($p<0.001$), the right knee more extended than left at 0–57% and again 64–100% ($p<0.001$), and the right hip angle differed for essentially 100% of stance ($p<0.001$). Differences in joint velocity for walking covered a substantial part of stance as well (ankle angular velocity differed at multiple intervals totaling ~80% of stance, knee for ~90% of stance, hip for ~70% of stance; $p<0.01$). Joint moment and power asymmetries in walking, while present, were slightly less pervasive than in running: the ankle moment was higher on the right from

18–50% (p<0.001), knee moment from 0–30% and 45–96% (p<0.001), hip moment from 0–53% and 60–92% (p<0.001). Ankle power differed 0–5%, 7–31%, 38–81%, 85–100% (p<0.001), knee power 11–28%, 37–53%, 82–91% (p<0.01), hip power 0–10%, 13–93% (p<0.001). These indicate that even in a simple gait like level walking, one limb was consistently doing more work (higher moments and generating more power) at certain times than the other.

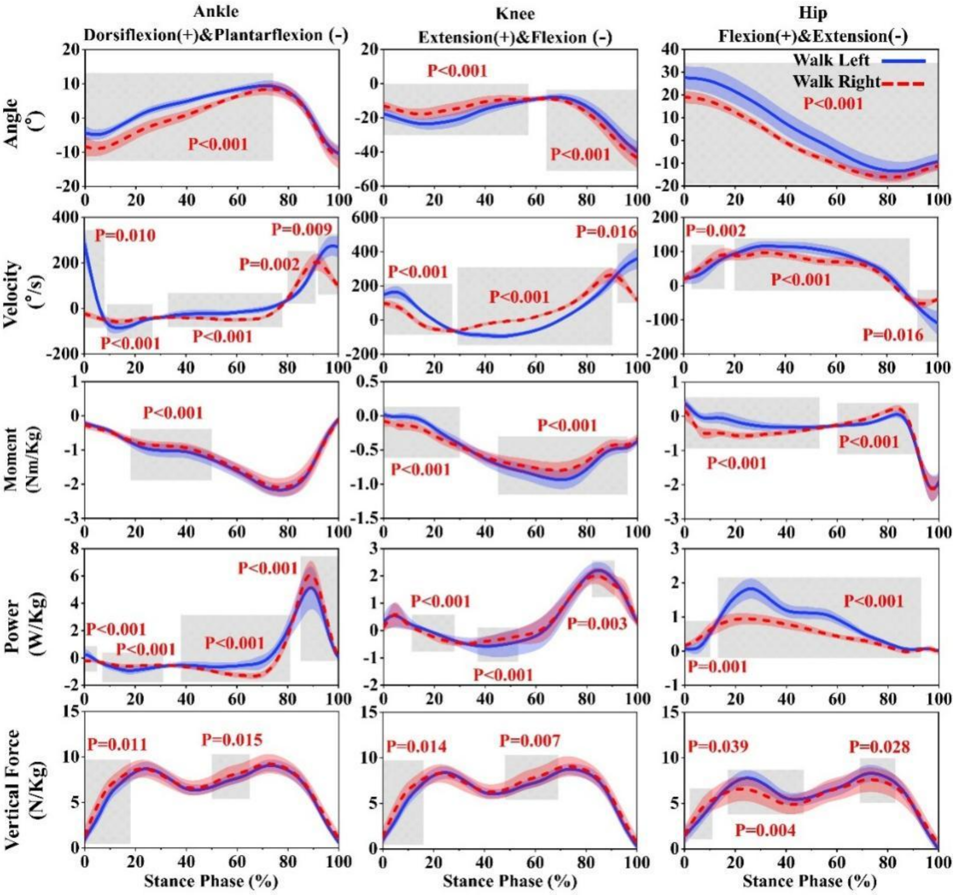


Figure 3.4.3 Illustration of the results between the left and right lower limb showing the statistical parametric mapping outputs for the angle, velocity, moment, power and force of the ankle, knee, and hip during the walking stance phase. Grey shades represent the significant differences and t-values of the statistical parametric mapping (SPM) for all participants (post hoc results; dashed red lines represent the results at p = 0.05).

During turning while walking, the asymmetries were again very pronounced – often even more so than in straight walking – because turning amplifies limb function differences (Figure 3.4.4). The right vs. left ankle angle differed for virtually the full stance (10%–100%, p<0.001), knee angle for 11%–76% (p<0.001), and hip angle for 0–53% of stance (p<0.001). Right ankle angular velocity exceeded left for ~0–19% and 21–86% (p<0.001), and other joints showed similarly wide differences in velocity (knee velocity differed over most of stance, hip velocity over more than half).

The turning walks also saw the knee joint moment significantly higher on one side for an exceptionally long duration (0%–98% of stance, p<0.001), indicating nearly the entire stance phase had unequal knee loading. Hip moment differed 0%–99% (p<0.001) as well. Joint power asymmetries spanned large portions too (ankle power differed 19%–64% and 74%–92%, knee power 2%–60% and 62%–100%, hip power 0%–81% and 82%–100%; p<0.001 in each interval). Even joint reaction forces in turning-walk were unequal (e.g., ankle and knee joint forces had notable differences at certain intervals). In summary, Group C exhibited systematic left-right biomechanical asymmetries: the dominant limb often showed greater joint angles, higher angular velocities, and produced larger moments and powers than the non-dominant limb. These differences were evident in straightforward gait and became even more extensive during turning maneuvers, underscoring that even among healthy young individuals, natural gait involves measurable inter-limb differences that are magnified by tasks requiring complex maneuvers or high forces.

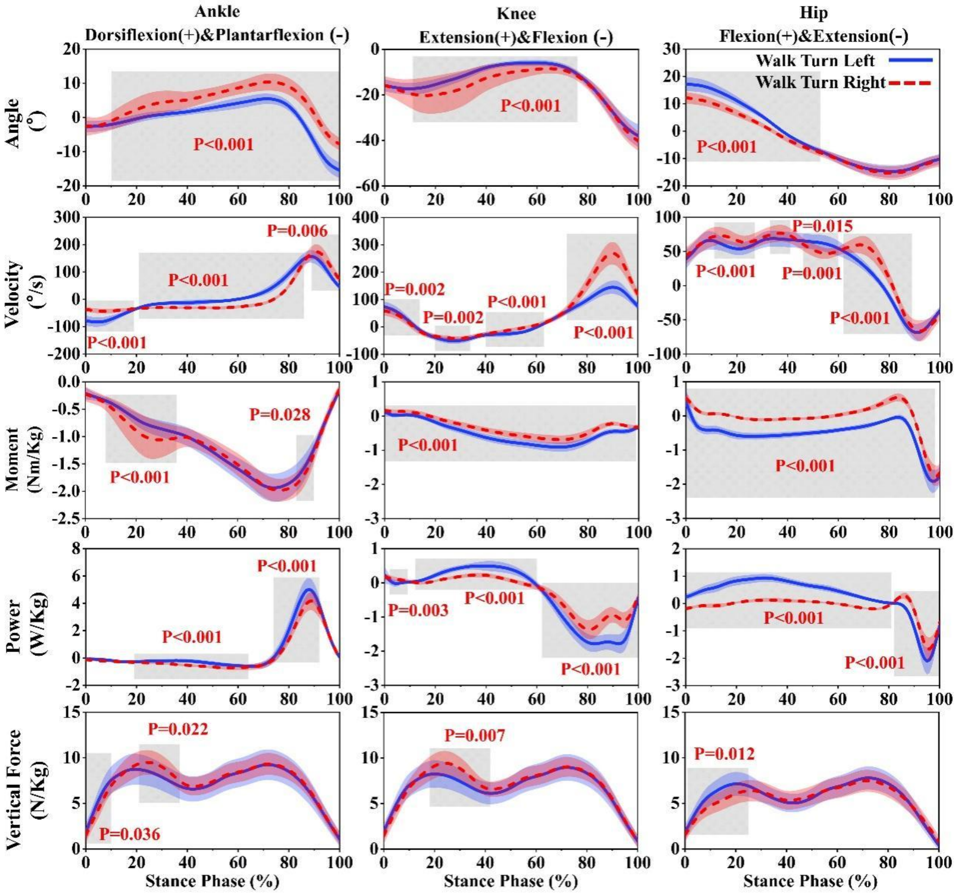


Figure 3.4.4 Illustration of the results between the left and right lower limb showing the statistical parametric mapping outputs for the angle, velocity, moment, power and force of the ankle, knee, and hip during the turning while walking stance phase. Grey shades represent the significant differences and t-values of the statistical parametric mapping (SPM) for all participants (post hoc results; dashed red lines represent the results at p = 0.05).

Table 3.4.1 Summary of the main asymmetry findings in Group A

Variable	Task	Direction of asymmetry	Stance phase	Main message
COP trajectory	Straight walking	Left foot more medial/pronated; right foot more lateral/supinated	Across most/all of stance	Clear but mild developmental laterality was present even in simple gait
COP trajectory	Straight running	Same left–right pattern, more evident than in walking	Across most/all of stance	Running amplified the existing COP asymmetry
FBI	Straight running	Left foot lower/more pronated than right	~18%–53%	Mid-stance foot-balance asymmetry became clearer under higher dynamic demand
Regional plantar pressure	Straight walking	Left M2 lower than right	~76%–95%	In walking, asymmetry was limited and highly localized
Regional plantar pressure	Straight running	Left M1 lower; left M4 and M5 higher than right	M1: ~10%–54%; M4: ~16%–35%; M5: ~5%–78%	Running redistributed asymmetry toward the lateral forefoot
COP / regional pressure	Turning tasks	Turn-direction-dependent inside/outside redistribution	Substantial portions of stance; e.g. M2 ~76%–92% in turning-walk; M4/M5 ~39%–88% in turning-run	Turning magnified localized asymmetry and altered load-transfer patterns

Table 3.4.2 Summary of the main SPD vs. control findings in Group B

Variable	Task	Direction of difference	Stance phase	Main message
COP / FBI / plantar pressure / GRF	Straight walking	No significant SPD–control difference	—	Low-demand gait was broadly similar between groups
Vertical GRF	Straight running	Controls > SPD in left foot	~22%–63%	Running revealed the clearest between-group force difference
Regional plantar pressure	Straight running	SPD > controls in midfoot; controls > SPD in hallux/toes/medial forefoot	Left MF: ~29%–57%; right MF: ~6%–100%; multiple distal-foot intervals in controls	SPD showed a midfoot-dominant and reduced distal push-off pattern
COP trajectory	Straight running	Controls more medial/pronated in right foot than SPD	~90%–100%	SPD showed reduced late-stance medial shift during push-off
FBI	Straight running	Controls showed greater right-foot pronation modulation than SPD	~47%–63%	SPD exhibited restricted stance-phase foot-balance adjustment
COP / GRF / FBI	Turning tasks	Differences mainly in right/inside foot and mostly phase-specific	COP: ~16%–69% during left turns; GRF: brief spikes at ~1%–2% and ~11%–15%; FBI: isolated intervals	Turning-related differences were present but weaker and more variable than running-related differences

Table 3.4.3 Summary of the main kinematic and kinetic asymmetry findings in Group C.

Variable	Task	Direction of asymmetry	Stance phase	Main message
Joint angles / velocities / moments / powers	Straight walking	Right/dominant limb generally greater or different than left/non-dominant limb	Variable, often shorter than in running	Baseline interlimb asymmetry was present even in simple gait
Joint angles / joint reaction forces	Straight running	Right/dominant limb generally greater or different than left	Ankle angle: 0%–71%, 85%–100%; hip angle: 0%–100%; hip force: 0%–72%, 75%–100%	Running expanded the duration and magnitude of asymmetry
Joint moments / powers	Straight running	Right/dominant limb generally greater than left	Multiple extended intervals across stance	Healthy trained adolescents showed broad dominance-related kinetic asymmetry
Joint angles / moments / powers	Turning while walking	Right vs. left differences extended through much of stance	e.g. ankle angle: 10%–100%; knee moment: 0%–98%; hip moment: 0%–99%	Turning greatly amplified interlimb role differentiation
Joint angles / moments / powers	Turning while running	Outside/right limb differed markedly from inside/left limb	e.g. ankle angle: ~18%–100%; knee angle: ~42%–100%; ankle moment: ~3%–84%; knee moment: ~0%–75% and 82%–100%	Broad asymmetry reflected braking–propulsion role separation during directional change

Taken together, the Group C results indicate that the observed asymmetries should be interpreted primarily as functional and task-dependent rather than as automatically pathological. In straight walking and running, the right/dominant limb generally showed greater kinematic excursion and kinetic output, consistent with natural dominance-related variability in healthy trained adolescents. During turning, these differences expanded across much larger portions of stance, which is biomechanically expected because the inside and outside limbs perform unequal braking, support, and propulsion roles during directional change. Therefore, the extensive stance-phase intervals reported here are best understood as reflecting the combination of functional limb dominance and task-specific mechanics. At the same time, because some asymmetries were broad and persistent, these variables may still be useful as potential monitoring indicators in athletic populations, although the present results alone do not justify interpreting them as injury-risk markers.

4 Discussion

4.1 Developmental Gait Asymmetry and Limb Dominance

The present findings confirm that even in typically developing children and adolescents, perfect bilateral symmetry in gait is rare. Small but consistent asymmetries were observed in foot loading and COP trajectories during straight walking – for example, the left foot tended toward a slightly more pronated (medial) pressure distribution, whereas the right foot showed a relative supination (lateral) bias. Such minor asymmetries align with the literature that healthy gait, while often assumed symmetric, usually exhibits subtle side-to-side differences [35–36]. Prior studies have documented measurable asymmetries in able-bodied gait, including differences in ground reaction forces and joint kinetics, even in the absence of pathology [19,35]. These asymmetries are typically quite small – often on the order of only 1–2% for spatiotemporal parameters in children [37–38] – and are generally considered functionally insignificant or “within normal.” Indeed, large-scale normative studies have found that healthy children maintain high symmetry in basic gait measures (e.g. step length or time differ by <1% between feet) across various speeds [37–38]. The results are consistent with this notion: during easy, straight-line gait, the magnitude of left–right differences were modest. This supports Hypothesis 1 (H1) that in simple conditions, interlimb differences would be small and dependent on the metric. Minor gait asymmetries can be considered a normal byproduct of physiological laterality and do not necessarily indicate dysfunction [35–36].

Limb dominance effects: Interestingly, the asymmetry observed in young children’s plantar pressure (left foot more medial pressure, right foot more lateral) appears linked to limb dominance. All participants were right-leg dominant, and the right foot tended to function more as a propulsive limb (showing higher toe-off pressure and a lateral COP roll-off), whereas the left acted more as a support/stabilization limb (greater midfoot/medial pressure). This pattern echoes the classic functional asymmetry hypothesis, which proposes that the dominant limb is often used for forceful propulsion or manipulation while the non-dominant limb provides postural support [13,35]. The findings accord with Polk et al. (2017), who found that healthy adults generate higher laterally-directed ground reaction forces with the dominant limb during walking [35]. Gao et al. (2022) similarly reported that limb dominance can affect plantar loading distribution: in healthy youth, the dominant foot may produce slightly greater impulses and different pressure patterns during gait [13]. Not all studies agree on the impact of laterality – for example, one study in 6 to 7-year-olds found an asymmetric plantar pressure pattern that was not attributable to foot preference [13]. Nonetheless, the balance of evidence (including the present data) suggests that limb dominance contributes to subtle biomechanical differences in otherwise symmetric gait [13,35]. These differences likely stem from developmental lateralization of motor control: children preferentially develop one leg for skillful tasks (e.g. kicking), which may lead to strength or control asymmetries [35,39]. Over time, this can manifest as the dominant limb exhibiting slightly greater push-off force, more pronounced lateral weight transfer, or larger joint ranges [13,35]. Importantly, in typical children these effects are very small and do not impair overall stability – the Group A participants had symmetric stride lengths and timing, indicating well-coordinated gait with only minute lateral biases. In fact, symmetry indices for step/stride in the young cohort would fall well within normative ranges (≈0.7–0.8 cm or <1% difference) [37–38]. Thus, consistent with prior literature, typically developing children demonstrate a high degree of gait symmetry at comfortable speeds [37], with limb dominance introducing only a mild bias that is usually negligible in functional terms [35,38].

It is worth noting that as children grow, their gait symmetry generally does not change dramatically under normal conditions – the 15-year-old adolescents (Group C controls) still showed some inherent asymmetries, much like the younger children. This aligns with longitudinal observations that gait symmetry, at least for basic spatiotemporal parameters, is established by mid-childhood and remains fairly invariant through adolescence [37–38]. For instance, previous work has found no significant age effect on symmetry between children and young adults walking at similar speeds [37–38]. The adolescent control data support this: small asymmetries persisted in parameters like foot loading pattern and joint motion, indicating that a perfectly symmetric gait is not a developmental end-goal even by the teen years. In fact, some evidence suggests healthy adults also retain minor limb differences due to habitual limb dominance [35]. In summary, a key point is that minor asymmetries are a normal feature of gait development rather than an anomaly [19,35]. The challenge is distinguishing benign asymmetry from pathologic asymmetry – a theme that will be expanded when discussing the special populations.

Taken together, the Group A findings support the interpretation that mild interlimb asymmetry in childhood is primarily a form of physiological developmental laterality rather than evidence of dysfunction [19,35–39]. The asymmetries were small, metric-dependent, and compatible with stable, well-coordinated gait, indicating that bilateral equivalence is not an obligatory feature of normal maturation [35,37–38]. Within this framework, limb dominance appears to introduce a subtle but functionally meaningful division of labor between support and propulsion [13,35]. Thus, the critical issue in pediatric gait is not the mere presence of asymmetry, but whether its magnitude, persistence, and task dependence exceed what would be expected in typical development.

4.2 Effects of Task Demands: Running and Turning Amplify Asymmetry

A central finding of this study is that gait asymmetry is highly context-dependent, becoming more pronounced under greater functional demands. Both Hypothesis 2 (that dynamic tasks like running/turning amplify plantar pressure and COP asymmetries) and Hypothesis 3 (that turning maneuvers elicit greater joint-level asymmetries in adolescents) were strongly supported by the results. This aligns with a growing consensus in biomechanics that symmetry is not a fixed trait but varies with speed and task requirements [37–38].

In Group A (healthy children), running had a clear amplifying effect on asymmetry compared to walking. During running, the divergence between left and right foot behavior increased substantially: the Foot Balance Index (FBI) showed a significantly larger difference (left more pronated vs right) in mid-stance when running, whereas during walking the FBI curves were much closer together. In running, the right foot's COP path deviated laterally (greater supination) during push-off, whereas the left foot's COP remained more medial (pronated) – a difference barely detectable in walking. Quantitatively, the left–right FBI difference became significant over ~18–53% of stance in running ($p<0.001$) but showed only minor, non-significant separation in walking. These findings corroborate prior reports that increasing gait speed tends to exacerbate asymmetries. Casabona et al. (2022) demonstrated that whole-body gait symmetry is high at comfortable speeds but can decrease when children walk faster, especially in groups prone to instability (children and older adults)[37]. Similarly, research has found that accelerating to a run can heighten asymmetrical kinetics; as running speed increases, individuals may unconsciously favor the dominant limb for stabilization and power [30,40]. The data agree: the mechanical demands of running (greater forces, shorter stance time) likely accentuate the intrinsic laterality in foot function. Biomechanically, higher speed reduces the time available for neuromuscular adjustments, so any lateral biases (e.g. one leg slightly stronger or more stable) manifest more clearly [38–39]. Additionally, running introduces flight and higher impact, which may require one limb to assume a more supportive role while the other drives propulsion – essentially amplifying the dominant/non-dominant dichotomy. The right (dominant) foot in healthy kids concentrated forces more at the forefoot (effective push-off), whereas the left foot bore more load medially and at the midfoot during running. This suggests that at high speeds the dominant limb "pushes off" more and the non-dominant limb "catches" more, increasing asymmetry in pressure distribution. Notably, these effects were task-specific: during walking, such differences were minimal, indicating that the children could manage a symmetric gait when demands were low.

Turning gait imposed even greater coordination demands, and accordingly some asymmetry amplification was also evident. Turning inherently creates an "inside" and "outside" leg with different roles, which can upset bilateral symmetry even in healthy individuals [19,41]. In the Group A turning trials, both feet changed their loading patterns depending on turn direction (a within-limb adaptation), but between-limb differences did not reach significance for most plantar pressure metrics (likely due to high variability). Still, qualitative trends indicated that asymmetry was present: for example, in a rightward turn (left foot inside), the left foot tended to have a more lateral COP trajectory (supination bias) whereas in a leftward turn (right foot inside), the right foot showed more pronounced pronation mid-stance. These mirrored shifts followed the mechanics of turning – the inside foot must accommodate body weight shifting laterally into the turn, often increasing supination, while the outside foot takes a wider, pronating step [10,19]. The results showed that the magnitudes of these COP asymmetries were larger in running turns than in walking turns, although due to variability and sample size the differences in Group A did not attain statistical significance. Nonetheless, the trend was clear that higher demand (running + turning combined) elicited the greatest asymmetry. This is in line with prior research: turning maneuvers are known to challenge balance and require complex interlimb coordination, often exposing subtle motor asymmetries that straight walking may not [10,19]. Even in confident infant walkers, recent work by Price et al. (2023) found that turning steps differ significantly from straight steps, with altered forefoot pressure and longer mediolateral COP path during turns [41]. In adults, Hu et al. (2023) reported distinct foot pressure distributions during 90° turns relative to straight gait, reflecting the unequal functional demands on the inner vs. outer limb [10]. Taken together, these studies and the findings underscore that task complexity amplifies gait asymmetry: children may appear nearly symmetric in easy forward walking, but when asked to cut or run, measurable imbalances emerge.

The Group C data (adolescent athletes) dramatically illustrate how turning and high speeds magnify asymmetry at the joint level. In straight walking, these adolescents already showed some bilateral differences in joint kinematics/kinetics (e.g. one limb doing slightly more work over parts of stance) – consistent with the minor asymmetries discussed above. However, during the 90° turning walk, asymmetries became very pronounced – often even more so than in straight walking. Nearly every major joint angle and moment exhibited significant differences between the left and right legs during turning (with the dominant right typically showing greater excursion or force). For instance, in a turning step the right ankle angle differed from the left for ~90% of stance, and right vs. left knee and hip moments were unequal for almost the entire stance phase of the turn. These extensive asymmetries were far larger than anything seen during linear gait. This aligns with Hypothesis 3 and mirrors previous findings that tasks requiring rapid redirection (cuts/turns) amplify interlimb differences in kinetics [10,19]. Turning induces an inherent asymmetry because one leg becomes the inside, braking and pivoting limb while the other leg becomes the outside, propulsive limb. Even skilled athletes show this. The results are comparable to those of Dixon et al. (2013) in children and to adult data on cutting maneuvers – both indicating that the biomechanics of a turn are not bilaterally equivalent [10,19]. It is notable that the adolescents' asymmetry during turning was greater than in straight running, despite running being faster. This suggests that the change in movement direction imposes a distinct asymmetrical load beyond just speed effects. Rapid turning requires one limb to handle elevated lateral forces (stabilizing the body through the turn) while the opposite limb may experience a different force trajectory or timing [10]. This task-driven divergence was precisely what was hypothesized: complex maneuvers elicit asymmetric coordination patterns even in otherwise symmetric individuals. From a control perspective, higher task demands may expose the "weak link" in the sensorimotor system – for example, the slightly less coordinated or slightly weaker limb will be taxed more and its performance will differ under stress [38–39]. The results reinforce that idea: asymmetry was minimal at low demand and maximal at highest demand.

In summary, these findings strongly support the concept of task-dependent asymmetry in gait. Minor limb differences are normally well-managed during simple locomotion, but as speed and maneuver complexity increase, the symmetry of gait can degrade measurably [10,37]. This has both theoretical and practical implications. Theoretically, it suggests that the neuromechanical control of gait has limited reserve for maintaining perfect symmetry under challenging conditions – some degree of lateralization is inevitable when the system is pushed to stabilize quickly or generate peak forces. Practically, it means that clinicians should assess gait under demanding conditions (e.g. faster speed, dual-task, directional changes) if the goal is to unmask subtle motor deficits or asymmetries [37,39]. A child who appears symmetric at a comfortable walk might show clear imbalances when asked to jog or turn rapidly. In a rehabilitation or sports context, this underscores the importance of task-specific evaluation: symmetric performance at low intensity does not guarantee symmetric capacity at high intensity. The data also hint that training in tasks like cutting or agility drills could be used to improve symmetry or at least to ensure neither limb is disproportionately underutilized in dynamic situations. The implications for performance and injury are revisited in Section 4.4, following discussion of how these task effects manifest in children with sensory processing challenges.

4.3 Sensory Processing Disorder and Altered Plantar Loading Strategies

A major objective of this study was to characterize how children with SPD differ in gait asymmetry and balance-related foot mechanics. Overall, the findings indicate that children with SPD demonstrate essentially normal, symmetric gait patterns in low-demand contexts, but they exhibit atypical and asymmetrical plantar pressure distributions under high-demand conditions. This supports Hypothesis 4 (H4) that group differences would be subtle during simple walking but amplify with dynamic tasks [15,42].

During straight walking at comfortable speed, the SPD group (Group B) showed plantar pressure and COP patterns largely indistinguishable from typically developing children. No significant differences in foot balance index or regional pressures were observed between SPD and control children in the walking task – both groups maintained the left-right characteristics described earlier, with SPD children mirroring the healthy group's minor asymmetries (e.g. a slight pronation tendency on the left foot) and overall symmetry indexes falling in normal range [15]. This is an important point: simply observing these children during easy gait might not reveal any impairment. Basic walking does not appear to overwhelm sensorimotor integration capacity, allowing gait symmetry comparable to peers. This aligns with clinical observations that many children with sensory processing challenges do not have obvious gait deviations in routine situations. Prior studies similarly have reported that on gross measures (e.g. walking speed, basic footprints), SPD or sensory-challenged children can perform comparably to typical children in simple tasks [15,42]. However, as soon as the task complexity increased – in this case, moving to running – clear differences emerged.

When running, SPD children adopted a distinctly different foot loading strategy compared to age-matched controls. The most striking difference was increased reliance on midfoot pressure and reduced use of the forefoot/toes during push-off among the SPD group. SPD children, while running, exhibited significantly higher pressure under the midfoot region and notably lower pressure under the toes and medial forefoot, relative to healthy children [15]. In practical terms, they ran with a flatter foot contact and less pronounced toe-off. Across almost the entire stance phase, SPD children bore more force in the midfoot than controls, whereas controls concentrated more force at the forefoot and toes especially in late stance [15]. Stated differently, the typically developing children achieved a strong, plantarflexed push-off with high toe pressures (indicative of an effective windlass mechanism and final weight transfer to the forefoot). In contrast, the SPD children maintained a more cautious loading profile – they kept more weight midfoot and did not shift as aggressively onto the forefoot at terminal stance [15]. This is quantitatively supported by the time-series statistical mapping, and it is highly consistent with previous research focusing on SPD gait. Yu et al. (2022) found that children with SPD demonstrated limited supination–pronation movement for shock attenuation in the foot complex and reduced ankle pronation to assist push-off and toe gripping during running [15]. The SPD runners exhibited this pattern: a restricted pronation range and less toe grip (lower toe pressure). These gait characteristics suggest that SPD children might be running with a stiffer, less finely controlled foot action – essentially not rolling through the foot as a typical child would. Instead of a heel-to-toe rocketed motion with adaptive pronation then supination, they seem to keep the foot more rigid (flatter) and push off with less forefoot force. Such a strategy could be a protective compensation for sensory deficiencies: if a child has difficulty processing proprioceptive or vestibular feedback, the quick, forceful weight shift onto the forefoot in late stance may be avoided because it is a less stable posture and requires precise sensory feedback. By keeping more weight midfoot, a broader base of support is maintained for longer, albeit at the expense of an efficient push-off. Essentially, SPD children trade propulsive efficiency for stability when running.

This interpretation is supported by the analysis of COP trajectories. While both groups showed the expected lateral-to-medial COP shift on each foot during running (reflecting normal pronation/supination patterns), the healthy controls had a slightly more pronounced medial shift (i.e. more pronation) on the right foot at push-off than the SPD children [15]. The SPD children's COP path remained more lateral in that phase, indicating reduced pronation (eversion). This matches the description by Yu et al. (2022) that SPD children have reduced ankle pronation to assist push-off [15]. In normal gait, the ankle/foot pronates then supinates to store and release elastic energy; reduced pronation may indicate incomplete engagement of this mechanism. The net result is likely a less powerful and less smooth push-off.

A plausible explanation is that SPD children have difficulties with the rapid sensorimotor feedback needed for dynamic balance. Sensory Processing Disorder often involves poor integration of proprioceptive and vestibular information, which are crucial for adjusting foot pressures during gait [15,42]. Running is essentially a series of controlled leaps, requiring quick postural corrections on each landing. In SPD, delayed or dampened perception of foot pressure and joint angle changes may compromise the finely tuned ankle strategies that typical children use [15]. As a compensatory strategy, a safer and more static foot placement may be adopted – contacting more flat-footed to increase ground contact area (hence the midfoot load) and avoiding extreme ranges of foot motion that are more difficult to regulate. This is analogous to patterns observed in other populations with sensory deficits. For example, children with cerebral palsy who have reduced plantar sensation often exhibit atypical loading patterns and reliance on midfoot/heel support [43]. Zarkou et al. (2020) reported that reduced foot sensation correlates with impaired balance and gait adaptations[43]. The

SPD cohort does not have gross sensory loss, but noisier or less reliable sensory integration may be present. Thus, the gait modifications can be interpreted as sensory-based motor adaptation.

Despite these adaptations, the SPD children in the study did not display gross motor inability – they could run and turn like their peers, and their overall timing (stride frequency, etc.) was similar to controls. However, the different loading strategy may indicate underlying balance challenges. Indeed, the literature consistently finds that children with sensory processing difficulties often have lower scores in balance and gross motor proficiency tests [42]. In this context, the plantar pressure patterns provide a mechanistic insight: by not shifting weight to the forefoot, SPD children possibly maintain more stable equilibrium (lower center-of-pressure excursion), which might prevent loss of balance at the cost of efficiency. During running, a more rigid foot (less pronation) and midfoot loading effectively stiffen the stance limb – akin to running with reduced ankle compliance. That could enhance stability (less risk of twisting an ankle or wobbling), but it also means less shock absorption and propulsive power.

Turning gait was also examined in SPD versus control children. Turns are even more balance-demanding, and SPD-related differences could therefore be expected to be magnified. The results showed that group differences in turning were present but more nuanced. Unlike in running, where clear pressure differences emerged, the turning trials did not yield as many statistically significant disparities in regional pressure between SPD and control group. Both groups found turning challenging (as evidenced by large variability in COP paths and pressures for all children during cuts). Several suggestive patterns were present: in some turning scenarios the healthy children appeared to use their forefoot more (higher peak toe/forefoot pressures) while SPD children kept a more even pressure distribution, but these trends were inconsistent and often not significant. A likely reason is that a sudden 90° turn imposed sufficient difficulty that all children adopted a more cautious approach – even typical children could not execute a turn with perfect symmetry or with the same ease as straight running [10,19]. In addition, the SPD sample was small (n=6) and heterogeneous in sensory profiles, limiting statistical power. Nonetheless, one clear difference in COP behavior was observed during turning: in leftward turns, the right foot (inside) COP path of SPD children was less pronated (more lateral) through mid-stance compared to controls [15]. This echoes the pattern seen in straight running and suggests that SPD children maintained a cautious strategy even during cuts – the inside foot was not pronated to the same extent as in typical children. The implication is that SPD children might turn more stiffly/upright, with reduced utilization of foot roll, potentially compromising dynamic stability.

Integrating these findings with existing literature: Children with SPD have been reported to have lower balance confidence and often show impaired postural responses under sensory-challenging conditions [42]. The present results provide evidence of how sensory issues translate into functional gait differences. The altered foot loading in SPD likely reflects an adaptive mechanism to mitigate sensory-processing deficiencies during motion. These differences became obvious primarily during dynamic tasks, consistent with the clinical observation that SPD-related motor issues (clumsiness, poor coordination) manifest especially during fast, complex actions like sports, rather than slow controlled actions [42]. In essence, higher task demands unmask the motor planning and balance difficulties associated with SPD, which might be latent during simple tasks [15,42]. The findings therefore support the rationale for testing children in real-life contexts – e.g. running, turning, hopping – to capture functional impacts of sensory processing problems [15,42].

It is also informative to compare the SPD results with those from children with developmental coordination disorder (DCD) or autism spectrum disorders, who often have sensory-motor integration issues. Studies on DCD have found that children with DCD exhibit greater gait asymmetry and variability than typical children when challenged with dynamic tasks [44]. Some work further indicates that gait in DCD remains less symmetrical than in peers even by adolescence, despite some improvement with age[44]. This echoes the SPD children in that both populations may rely on irregular gait patterns under duress. However, a distinction emerged: the SPD children did not show large asymmetries in the spatiotemporal domain (step lengths/times remained symmetric). In DCD, some studies have reported measurable asymmetries in step length or timing [44]. The difference could be related to severity: DCD is a motor disorder diagnosis and may have greater motor impact than SPD. In the SPD group, asymmetries were more evident in force distribution (pressure patterns) than in gross step outcomes. This suggests relatively preserved higher-level gait timing, with alterations at the level of sensory-guided modulation of foot loading.

In turning, SPD children did not appear markedly unsteady – none lost balance or stopped – but turning behavior may have been slower or more cautious. Video review indicated that some SPD children used an added side step or wider base when initiating the turn, which could reflect an intentional stability strategy. Future work should quantify turn time, step counts, and detailed kinematics to corroborate these observations.

In summary, children with SPD in the study: (i) performed straight walking similarly to typical children (no significant asymmetry or imbalance); (ii) showed clear differences in running: a flatter, less forceful push-off (midfoot-weighted, less toe-off pressure) and a tendency to limit foot pronation, presumably to enhance stability[15]; (iii) demonstrated subtle differences in turning (e.g. reduced pronation of the inside foot), though not as large or consistent as in running; and (iv) maintained symmetry in gross gait timing but revealed altered pressure distribution under high demand, consistent with deficits in sensory-guided modulation of force rather than basic rhythm generation.

These findings have important implications. First, they support the inclusion of dynamic tasks in clinical evaluation of children with SPD – standard gait assessment on level ground may appear normal, potentially underestimating motor difficulties [15,42]. Second, they highlight targets for intervention: therapies that improve ankle proprioception and the ability to utilize the forefoot in push-off may be beneficial. Encouraging a more effective toe-off could be incorporated into sensory-motor training (e.g. balance exercises that promote controlled dorsiflexion–plantarflexion and weight transfer). The midfoot-loading tendency suggests reduced calf engagement or an intentional avoidance related to sensory feedback. Strengthening and retraining push-off (hopping, skipping, etc., in a sensory-rich environment) may help develop a more normalized pattern. Evidence indicates that balance and agility training can improve postural control in children with sensory integration problems [42], and the current results provide a biomechanical rationale for such interventions.

It is also worthwhile to consider the broader impact of these gait differences on activity and participation. A child with SPD who runs with less efficient mechanics may fatigue faster or be slower, potentially affecting willingness to engage in sports or play. Parents and therapists often report that these children avoid playground games or struggle in team sports [42]. The gait adaptations observed could partially explain those observations. While the SPD group was small, all were children without major orthopedic or neurologic issues, yet gait patterns under dynamic conditions were suboptimal. Over time, such patterns might predispose to certain injuries (e.g. flatter-foot strike increasing shock through the shank, potentially stressing joints). However, given the young age and moderate activity levels, injury-risk conclusions cannot be drawn. Literature in athletic populations suggests that asymmetries >~10–15% in force or motion can elevate injury risk [45]. The asymmetries observed in SPD versus typical children (e.g. elevated midfoot pressure) warrant longitudinal examination to test whether adolescents with persistent sensory issues show higher rates of ankle or knee problems.

It could be emphasized that the observed gait differences in SPD children reinforce the concept of a sensory-motor spectrum. These children are not grossly impaired – everyday gait is managed – but under strain motor output is measurably altered by sensory processing deficits. The study contributes by demonstrating concrete gait metrics (plantar pressure/COP) that correlate with sensory processing status, supporting plantar pressure analysis as a tool for detecting subtle balance strategy differences in special populations [15,36]. The next section relates these findings to the athletic adolescent data and discusses implications for performance and injury, thereby situating asymmetry across typical development, SPD, and high-performing athletes.

Taken together, the Group B findings are best interpreted as sensory-driven stability compensation rather than as a generalized gait deficit. Children with SPD were broadly comparable to controls during walking, but under running they adopted a flatter, midfoot-dominant and less pronated loading strategy, indicating reduced reliance on rapid distal push-off and dynamic medial–lateral modulation [15,42]. The strongest group differences were therefore task-dependent and were expressed mainly in running, with turning showing subtler and more variable effects. These effects were mainly phase-specific rather than global, reinforcing the view that low-demand gait assessment may fail to detect clinically meaningful motor-control alterations in SPD [15,42]. In this sense, SPD-related asymmetry was not primarily a problem of basic rhythm generation, but of how sensory information was used to regulate load transfer when dynamic stability demands increased.

4.4 Broader Implications: Asymmetry in Athletic Performance and Injury Risk

The evidence from the adolescent athletes (Group C) highlights that even among healthy, trained individuals, functional asymmetry is a natural occurrence – and it can be magnified by specific athletic demands or long-term training specializations. All 15 adolescent athletes in the study were right-foot dominant (as is common), and consistent asymmetries favoring the dominant leg were observed across many joint kinematic and kinetic measures. For example, during straight running the right leg exhibited greater ankle plantar-flexor moment and knee extensor moment over substantial portions of stance. The right leg also generated more mechanical power at the ankle, knee, and hip in key phases of stance. These differences imply that the dominant limb contributed more to propulsion and support – essentially doing more "work" – whereas the non-dominant limb was slightly less active in those roles. Such asymmetries were present not only in running but even in walking (though smaller in magnitude). Far from being perfectly bilaterally symmetric machines, the adolescent athletes showed that one side of the body can systematically produce more force or motion than the other, corroborating a body of research on interlimb differences in sports [40,45].

Studies in athletic populations have reported similar findings: athletes often exhibit between-limb differences in jump kinetics or strength measures. The data fit within this scope – e.g. the right hip generated more extensor moment than the left at certain times, and the right knee had greater peak power than left in late stance. These values are not extreme, but they are consistent. It appears that long-term habitual limb dominance (the right leg being used preferentially in kicking, jumping off, etc.) leads to measurable side-to-side differences in strength and coordination by adolescence [13,30]. Gao et al. (2020) noted that prolonged running and fatigue can accentuate asymmetry in lower-limb joint variables [30]. One limb may become relatively more fatigued or alter its mechanics more. In the athletes, the dominant limb may have more developed musculature or motor control due to years of sport, thereby handling slightly more load.

The turning data for Group C took this a step further: turning while walking unleashed large asymmetries that were not evident in normal walking. Nearly the entire stance phase showed significant joint moment differences between limbs in turning. This indicates that during complex movements, these youths rely even more heavily on one limb (likely the dominant) for force generation and stabilization. Such reliance could stem from subtle differences in limb function – for example, slightly better balance or force capacity in the dominant limb – producing preferential use during challenging maneuvers. Athletes often develop lateralized techniques (e.g. preferential kicking leg; take-off leg), which may increase strength asymmetries and reinforce movement asymmetry over time.

The findings have practical relevance for athletic training and injury prevention. Significant interlimb asymmetries have been associated with elevated injury risk in sports [45–46]. A commonly cited threshold is that >10–15% difference in limb output (strength, power, etc.) can increase risk of lower-limb injury. In the adolescent athletes, some measures (like hip power output) approached or exceeded the 10% asymmetry level, suggesting that even "healthy" asymmetries might warrant attention if large. Targeted training can reduce lower-limb asymmetry in athletes; unilateral plyometric training, for example, has been shown to improve symmetry in jump performance [45]. Thus, observed asymmetries are not necessarily immutable and may be mitigated with specific interventions if desired. From a performance standpoint, small asymmetries are not necessarily detrimental and may sometimes reflect beneficial specialization (for example, a soccer kick). However, for gait-related and lower-limb sports, larger asymmetries have been linked to impaired performance and increased injury risk [40]. The asymmetry data can therefore be used as baseline metrics for monitoring. Balanced training that addresses weaker-limb deficits may reduce asymmetry and potentially lower injury incidence [40,45]. In rehabilitation, a common discharge criterion after injury is restoring limb symmetry to within ~10%. The adolescent data underscore that some uninjured athletes naturally deviate by up to 10%; therefore, failure to restore symmetry post-injury may imply even larger functional deficits, consistent with evidence linking incomplete criteria attainment to higher re-injury risk (e.g. ACL graft rupture risk) [46].

From a developmental perspective, the presence of asymmetry in proficient adolescents indicates that perfect symmetry is not the normal outcome of motor development. Each individual may find a unique balance – often favoring one side in subtle ways – to optimize activities. Girard (2025) discussed that the "myth of perfect symmetry" is giving way to the reality that successful performance may entail asymmetry [47]. The results support this perspective: the athletes were active and presumably successful, yet movement was not fully symmetric. The key distinction is whether asymmetry is functional or maladaptive. The asymmetries observed did not appear to hinder performance in the tests; however, if asymmetries were to grow larger (e.g. one leg doing 20–30% more work), uneven fatigue and injury risk might increase.

Comparing Group C (athletes) with Group B (SPD) provides a contrast in mechanisms: in athletes, asymmetry stems from purposeful or training-related dominance, whereas in SPD, asymmetry (or altered loading) stems from sensory and motor control limitations. In both cases, the outcome is an imbalance in contribution between limbs, but the underlying causes differ. Longitudinal research could test whether early sensory-motor interventions in SPD improve movement patterns and reduce potential risk during later sports participation.

Lastly, the results have methodological implications for gait analysis: time-series analyses (such as SPM) were valuable for revealing phase-specific asymmetries. Traditional discrete measures (e.g.

peak force) can miss timing-dependent effects. Asymmetries were phase-dependent – one limb could differ in early stance while the other differed in late stance – and analysis across the entire stance phase captured the full temporal profile [15,36]. Future gait asymmetry studies, particularly for dynamic tasks, may benefit from similar continuous analysis approaches.

Taken together, the Group C findings indicate that widespread joint-level asymmetry in healthy adolescent athletes is best interpreted primarily as training-driven kinetic specialization superimposed on functional limb dominance, rather than as an automatically pathological state [30,40,45,47]. The broad stance-phase differences observed during turning are biomechanically consistent with unequal braking, support, and propulsion roles between limbs, especially in athletes exposed to repeated unilateral sport demands [10,19,40]. At the same time, these asymmetries remain relevant for monitoring, because when their magnitude becomes excessive or persistent they may shift from functional specialization toward maladaptive imbalance and elevated injury risk [45–46]. Thus, athletic asymmetry should be interpreted in relation to task, training background, and magnitude, rather than by a simple symmetric-versus-asymmetric dichotomy.

Overall, the three cohorts indicate that gait asymmetry should not be interpreted as a single phenomenon with a single meaning. Rather, this study supports a mechanistic framework in which asymmetry takes different forms depending on developmental stage, sensory–motor capacity, and task demand. In Group A, asymmetry was generally mild and reflected physiological developmental laterality superimposed on limb dominance [13,19,35–39]. In Group B, asymmetry was not consistently increased in all conditions, but the organization of loading changed under dynamic tasks, indicating sensory-driven stability compensation [15,42]. In Group C, asymmetry was broader and more persistent at the joint level, consistent with training-driven kinetic specialization and functional limb-role differentiation [10,30,40,45]. This comparison is important because it shows that similar surface-level observations—namely, left–right differences—can arise from different underlying mechanisms and therefore require different interpretations. Table 4.4.1 strengthens the thesis-level argument that asymmetry is not inherently pathological, nor is it adequately described by a single symmetry score. Instead, its meaning depends on whether it reflects normal developmental laterality, compensatory sensory–motor adaptation, or functional athletic specialization. By distinguishing these mechanisms within one framework, this study extends gait asymmetry research beyond simple left–right comparison and toward context-sensitive interpretation.

In conclusion, the novel contribution of this thesis lies in integrating developmental, clinical, and performance-based asymmetry within a single biomechanics framework rather than treating them as separate observations. First, this study demonstrates that gait asymmetry is fundamentally task-dependent and phase-specific, becoming most informative under running and turning conditions

[10,12,20,36]. Second, it shows that low-demand walking can mask clinically meaningful differences in children with SPD, whereas dynamic tasks reveal altered load-transfer strategies consistent with sensory-driven compensation [15,42]. Third, it links foot-level plantar loading and COP behavior with joint-level asymmetry, thereby extending interpretation from local foot mechanics to whole-limb functional roles. Finally, by applying time-series analysis across multiple locomotor tasks, this study advances a more nuanced model in which asymmetry can be physiological, compensatory, or performance-related depending on context. Collectively, these contributions strengthen both the theoretical understanding of pediatric gait asymmetry and the practical basis for clinical assessment, intervention design, and athletic monitoring.

Table 4.4.1 Comparative synthesis of asymmetry mechanisms across cohorts

Cohort	Predominant asymmetry pattern	Primary mechanism	Tasks where most evident	Interpretation	Practical implication
Group A (healthy children)	Mild COP/FBI and regional loading laterality	Physiological developmental laterality with subtle dominance-related limb-role bias	Running and turning > walking	Expected and largely functionally benign	Provides a normative developmental reference for task-amplified asymmetry
Group B (SPD children)	Midfoot-dominant loading, reduced distal push-off, restricted COP/FBI modulation	Sensory-driven stability compensation	Strongest in running; subtler and more variable in turning; minimal in walking	Adaptive but clinically meaningful under dynamic demand	Supports dynamic task assessment and targeted sensory–motor intervention
Group C (healthy adolescent athletes)	Broad joint kinematic and kinetic asymmetry, especially during turning	Training-driven kinetic specialization plus inside–outside limb role differentiation	Turning > running > walking	Functional dominance unless excessive or persistent	Useful for performance monitoring and injury-risk surveillance

4.5 Limitation Statements

In interpreting the findings of this thesis, several limitations should be considered. They largely reflect pragmatic choices needed to ensure experimental control and high-quality measurements in children. These limitations do not negate the main contribution of this work—characterizing gait, plantar loading, and balance strategies associated with sensory processing difficulties under standardized tasks—but they do define the boundary conditions for generalization and highlight clear priorities for future studies.

Single experimental environment (e.g., only one pressure plate). First, all gait and plantar-pressure outcomes were collected in a single laboratory environment using one pressure plate system. A controlled setup is advantageous for isolating task effects and reducing confounders such as variable surface properties, footwear differences, distractions, and inconsistently defined walking bouts. However, a single plate typically captures only a limited number of steps per condition, which constrains the characterization of step-to-step variability and may under-sample rare events (e.g., occasional instability-related adjustments) that could be informative in children with sensory processing difficulties. In addition, participants may modify foot placement when they anticipate stepping onto a measurement area ("targeting"). Although force plate targeting has been reported to have minimal effect on spatiotemporal gait measures and their variability in young healthy participants under certain protocols [48], subtle adaptations cannot be fully excluded in pediatric or clinical cohorts, particularly for tasks that increase attentional demands. Our procedures (practice trials, consistent instructions, and standardized starting positions) were designed to reduce this risk, but some degree of context dependence may remain.

A second consequence of relying on one instrument is that device-specific characteristics can influence derived pressure variables and limit comparability across laboratories. Pressure platforms differ in sensor technology, spatial resolution, sampling frequency, and calibration routines, and these differences may affect peak pressure and center-of-pressure measures. Platform reliability has been shown to vary across outcomes and setups, underscoring the importance of standardized protocols and sufficient trials for stable estimates [49]. Relatedly, different pressure measurement approaches should not be assumed interchangeable. Comparative evidence indicates that in-shoe versus platform measurements (and shod versus unshod conditions) can yield meaningfully different pressure magnitudes, timing variables, and center-of-pressure displacement patterns, supporting the need for a consistent collection method when interpreting plantar-pressure outcomes [50]. Methodological reviews further emphasize that protocol decisions (including calibration and step-collection approaches) can materially affect pressure outputs, and that in-shoe systems may be preferable when the goal is to capture multiple steps during daily living or sport-specific tasks [51]. Finally, generalizability beyond the laboratory may be constrained by the clinical testing context itself. Wearable-sensor studies in children have shown that gait characteristics assessed in a clinic or laboratory can differ from gait observed during daily life, illustrating the distinction between supervised "capacity" and unsupervised "performance" [52]. Future work should therefore examine whether the present findings replicate across multiple environments and measurement modalities, and whether task-related effects persist during longer walking bouts or across more complex real-world surfaces.

Small SPD subgroup size. Second, the SPD subgroup was relatively small (n = 6), which likely reduced statistical power for subtle or task-variable effects and limits the generalizability of the between-group findings. Although averaging repeated successful trials per participant helped reduce within-subject variability, the modest subgroup size means that non-significant results—particularly in the more variable turning conditions—should be interpreted cautiously and should not be taken as evidence of equivalence between groups. At the same time, the restricted subgroup was a pragmatic consequence of the difficulty of recruiting children who met the inclusion criteria and could complete the full biomechanical protocol under standardized laboratory conditions. Future studies should therefore recruit larger and more phenotypically characterized sensory processing cohorts in order to confirm the robustness, consistency, and external validity of the present between-group findings.

Exclusion of other neurodevelopmental disorders (e.g., DCD, ASD). Third, this thesis focused on SPD/sensory processing difficulties and did not explicitly include other neurodevelopmental comparison groups such as developmental coordination disorder (DCD) or autism spectrum disorder (ASD). This decision helped maintain a targeted mechanistic focus on sensory integration constraints, but it limits cross-diagnostic specificity. Motor and gait differences are also evident in DCD, where children can display altered gait and postural strategies compared with typically developing peers [53]. Likewise, reviews of ASD gait research describe systematic group-level deviations in spatiotemporal parameters and kinematics, frequently interpreted as stability-seeking or neuromotor differences [54]. In addition, symptom-level overlap is common: when motor performance is evaluated against DCD diagnostic criteria, a substantial proportion of children and adolescents with ASD may meet criteria for co-occurring DCD [55]. Together, this literature indicates that some gait and balance features observed in SPD may also occur in other neurodevelopmental profiles, potentially via different pathways (e.g., primary coordination constraints versus sensory modulation/integration constraints). Accordingly, the current results should be interpreted as characteristics associated with the recruited SPD phenotype, rather than as SPD-specific "signatures" that can be generalized across neurodevelopmental disorders. Future studies should broaden sampling to include DCD and ASD cohorts (and other relevant profiles), apply standardized diagnostic assessments alongside sensory phenotyping, and test whether biomechanical outcomes are best explained by sensory subtype, motor coordination status, or their interaction.

No longitudinal follow-up or intervention tracking. Fourth, the study design was cross-sectional and did not include longitudinal follow-up or post-intervention monitoring. Therefore, the observed group differences and task effects cannot be interpreted as developmental trajectories or causal relationships. This limitation matters in pediatric biomechanics because maturation, growth, and motor learning can reshape gait and balance strategies over time. Longitudinal follow-up work in sensory processing research suggests that sensory-related challenges can evolve across development and may decrease in severity for a subset of individuals [56]. Without follow-up, it is not possible to determine whether the biomechanical patterns observed here reflect stable traits, delayed maturation, or compensatory strategies that evolve with age and participation.

Similarly, this thesis did not test whether therapeutic interventions can modify plantar loading, gait biomechanics, or balance strategies in children with sensory processing difficulties. Randomized trials of manualized occupational therapy interventions targeting sensory difficulties (most commonly studied in ASD) indicate that structured treatment can improve functionally meaningful outcomes under rigorous designs [57]. However, because intervention effects were not measured here, the present results should be viewed as a baseline characterization rather than evidence for modifiability. Future work should incorporate longitudinal and intervention designs to evaluate which biomechanical outcomes are sensitive to change and whether they track clinical improvement.

In summary, this thesis should be interpreted within four primary constraints: (1) one controlled laboratory environment and one pressure plate system, (2) a relatively small SPD subgroup, (3) a focused SPD cohort without explicit inclusion of DCD/ASD comparison groups, and (4) a cross-sectional design without longitudinal or intervention tracking. Framed appropriately, these limitations are not fatal weaknesses; rather, they clarify where the conclusions are strongest and provide a roadmap for extending this research toward broader generalizability and clinical translation.

5 Conclusions and future works

In this discussion, findings were synthesized across developmental, clinical, and performance contexts. Several key conclusions emerge: (i) Minor gait asymmetries are a normal feature of development. Healthy children and adolescents exhibit small but consistent left-right differences. These asymmetries likely relate to limb dominance and individual limb roles, and are usually functionally benign [35,38]. (ii) Task demands amplify asymmetry. Higher speeds and directional changes (running, cutting) led to larger asymmetries in both plantar pressure and joint mechanics. This reflects the limits of neuromuscular control under challenge – even able-bodied individuals show magnified asymmetry when stability demands are high [10,40]. For researchers and clinicians, this underscores the importance of context when evaluating gait symmetry. (iii) Children with sensory processing difficulties demonstrate adaptive but asymmetrical gait strategies under dynamic conditions. They can appear normal in easy gait, but during running their altered foot loading (flatter, midfoot-biased, reduced push-off) and during turning their limited weight shift differentiate them from typical children. These findings connect measurable biomechanical differences to underlying sensory integration issues, affirming that sensory-driven motor deficits become evident in challenging tasks [15,42].

Asymmetry per se is not always detrimental, but excessive asymmetry can be a concern. In adolescent athletes, inherent asymmetries likely stem from training and dominance. A certain degree of asymmetry may be inevitable or even beneficial for specialization. However, larger asymmetries (exceeding ~10–15%) have been associated with decreased performance and increased injury risk [45–46]. Monitoring and addressing asymmetries through training (e.g. unilateral strength programs) may improve outcomes, as suggested by recent research [45]. The data provide reference values and support using tools like pressure analysis and continuous time-series methods to quantify asymmetry for such purposes [15,36].

Looking forward, several avenues for future work are apparent. Longitudinal studies could examine whether children with SPD who receive targeted intervention (sensory integration therapy, balance training, etc.) show improvements in dynamic gait symmetry and whether that correlates with better functional outcomes (e.g. greater participation in physical play). It would also be worthwhile to investigate gait asymmetry in other special populations using this approach – for example, children with autism spectrum disorder or ADHD (who often have sensory modulation issues) might display similar gait adaptations as the SPD cohort, a hypothesis that requires verification. On the performance side, future research could aim to define acceptable vs. problematic asymmetry thresholds in youth athletes. While asymmetry is normal, consensus on injury-relevant thresholds remains limited [45–46]. Prospective studies tracking athletes with measured asymmetries over a season would be valuable.

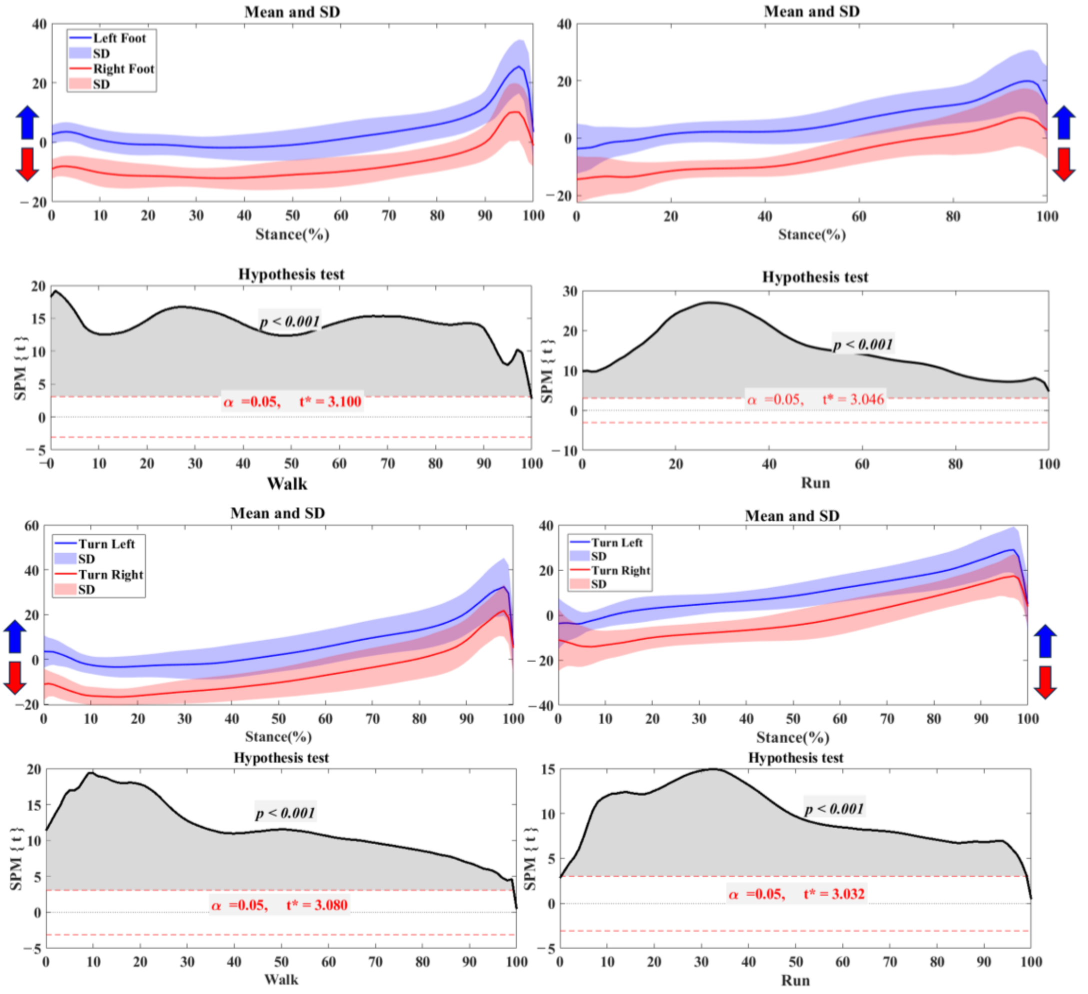
Another technical future direction is to incorporate musculoskeletal modeling to understand how asymmetrical external measures (pressure, GRF) translate to internal loads on joints and tissues. For instance, SPD children's midfoot-heavy gait could alter midfoot bone loading or Achilles tendon stress; athlete asymmetry could lead to consistently higher impulse on one knee, potentially predisposing to unilateral issues. Modern simulation tools could estimate joint contact forces or ligament strains for each limb using the data as input. This would deepen biomechanical insight and connect asymmetry with potential tissue-level consequences [40].

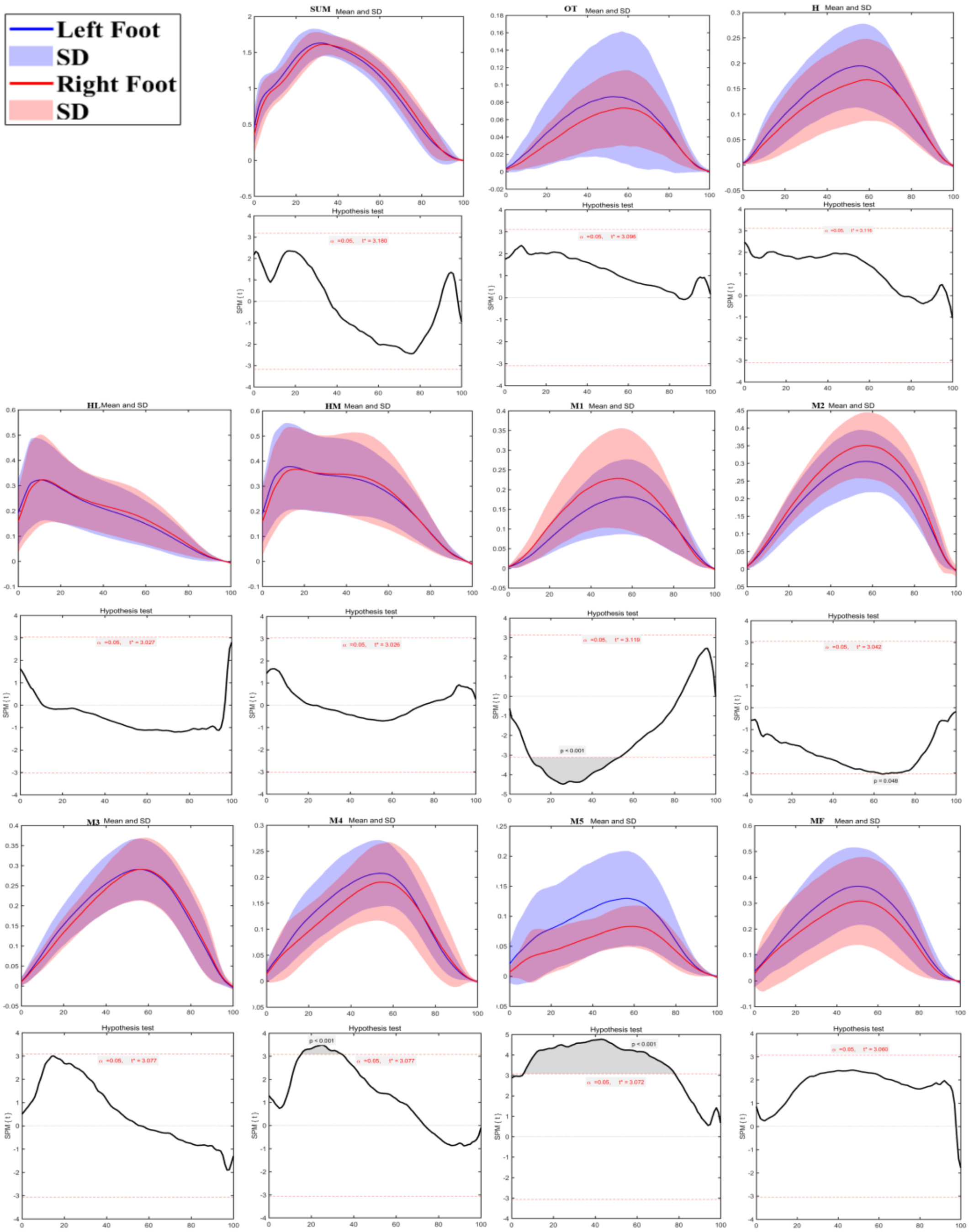
In conclusion, this study's discussion illustrates that gait symmetry is a continuum influenced by developmental stage, task demand, and individual sensory-motor capacity. Small asymmetries are part of typical maturation and reflect natural laterality [35], but challenging conditions amplify these differences, which can expose underlying impairments in populations like SPD or manifest in unique ways in athletes. By examining when and how asymmetry arises, the findings provide theoretical insight into gait control and practical guidance for clinical assessment (testing under stress), intervention design (targeting the phase or side of deficit), and athletic training (monitoring and addressing extreme asymmetries). Ultimately, the ability to maintain appropriate symmetry – or purposeful asymmetry – is a hallmark of adaptable, robust gait. Ensuring that individuals can achieve that adaptability, whether through therapeutic intervention in a child with SPD or balanced training in an athlete, may maximize both safety and performance in locomotor activities.

Thesis points

1st Thesis point:

Task-dependent asymmetry is a typical feature of development, with COP and plantar loading becoming measurably more asymmetric as coordination demands increase. Task demand strongly shapes developmental gait asymmetry, and time-series analysis shows that many differences are phase-specific rather than global. Using one-dimensional statistical parametric mapping across 0–100% stance, healthy children demonstrate minimal asymmetry during low-demand gait but clear task-related shifts as speed and maneuvering increase. COP trajectories show a consistent left–right offset across the entire stance phase in both walking and running ($p<0.001$; Figure 3.1). Plantar loading during straight walking remains close to symmetric, with only a late-stance M2 difference (approximately 76–95% of contact, $p<0.01$). Running amplifies and redistributes loading, with lower left M1 pressure in early stance (about 10–54%, $p<0.01$) but higher left lateral forefoot loading (M4: ~16–35%, $p<0.01$; M5: ~5–78%, $p<0.01$; Figure 3.10). Turning introduces direction-specific control demands: left-turn and right-turn stances show opposite medial–lateral COP shifts, producing significant COP differences over substantial portions of stance ($p<0.001$; Figure 3.2). Overall, asymmetry becomes most evident when coordination and balance demands rise.



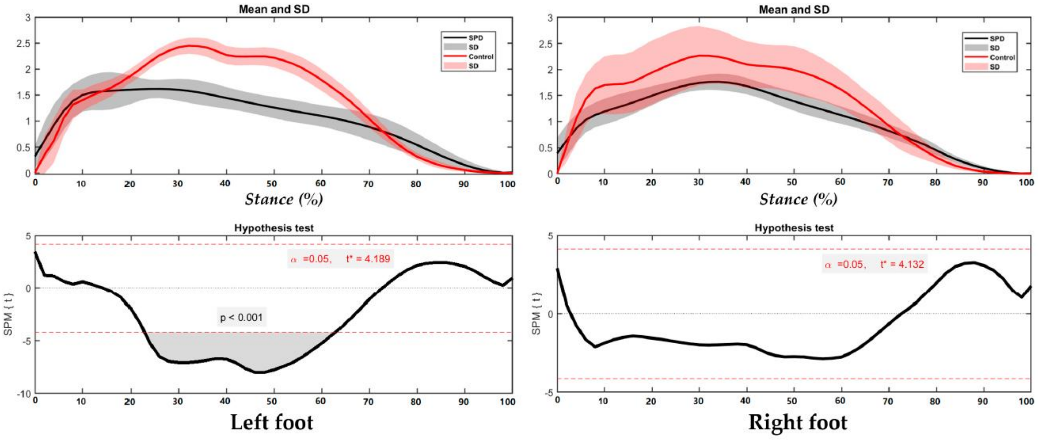


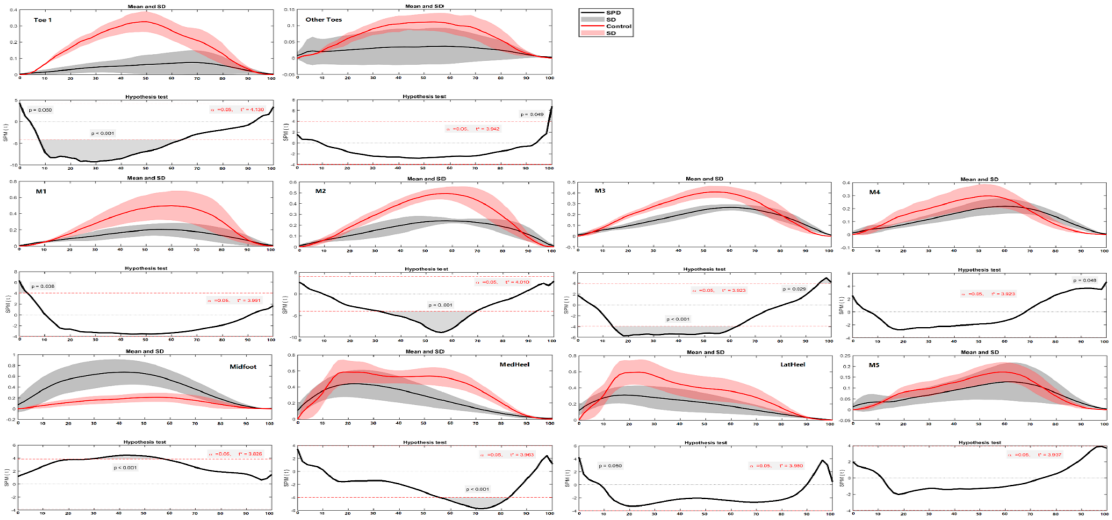
Related articles to the 1st thesis point:

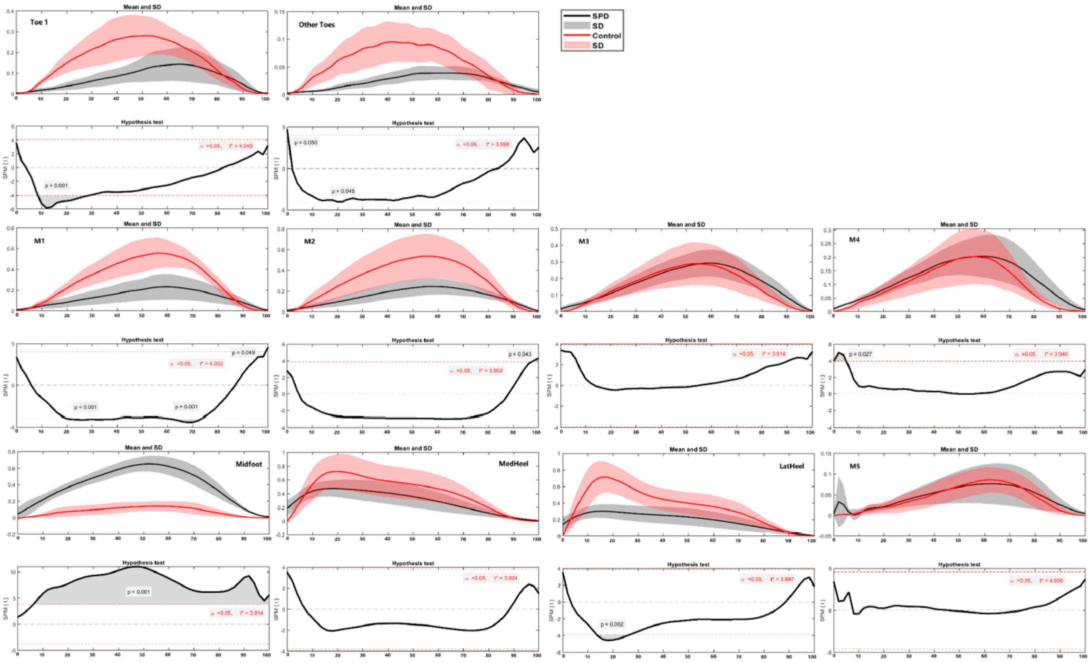
1. **<u>Liu, W.,</u>** Mei, Q., Yu, P., Gao, Z., Hu, Q., Fekete, G., István, B., & Gu, Y. (2022). Biomechanical Characteristics of the Typically Developing Toddler Gait: A Narrative Review. Children, 9(3), 406. **IF: 2.4, Q2**
2. **<u>Liu, W.,</u>** Xu, L., Wu, H., Wang, Y., Jiang, H., Gao, Z., Jánosi, E., Fekete, G., Mei, Q., & Gu, Y. (2025). Bilateral Asymmetries of Plantar Pressure and Foot Balance During Walking, Running, and Turning Gait in Typically Developing Children. Bioengineering, 12(2), 151. **IF: 3.7, Q2**

2nd Thesis point:

SPD-related gait differences are largely hidden in walking but become clear in running, where a midfoot-dominant loading strategy replaces distal push-off patterns seen in controls. Clinical differences in sensory–motor control are most visible under high-demand tasks. In the SPD versus typically developing cohort, level walking shows no significant between-group differences in total plantar force profiles or regional pressure distributions, indicating that gross plantar metrics can appear normal when stability demands are low. During running, healthy controls generate a higher left-foot vertical ground reaction force for a sustained interval (approximately 22–63% of stance, $p<0.001$; Figure 3.14) and display stronger distal loading. Controls show higher pressures under the hallux (Toe 1: ~7–62% stance) and medial forefoot regions (M2: ~33–69%; M3: ~14–62%), while SPD children show a consistent midfoot-dominant strategy. Midfoot pressure is higher in SPD children in the left foot during mid stance (~29–57%, $p<0.001$) and in the right foot for almost the entire stance (~6–100%, $p<0.001$; Figures 3.16–3.17). Turning tasks produce more variable group effects, with only brief GRF spikes in SPD at initial contact (~1–2%) and early mid-stance (~11–15%). Overall, the findings support task-specific assessment, where running reveals reduced push-off emphasis and altered load transfer consistent with balance-first strategies in SPD.





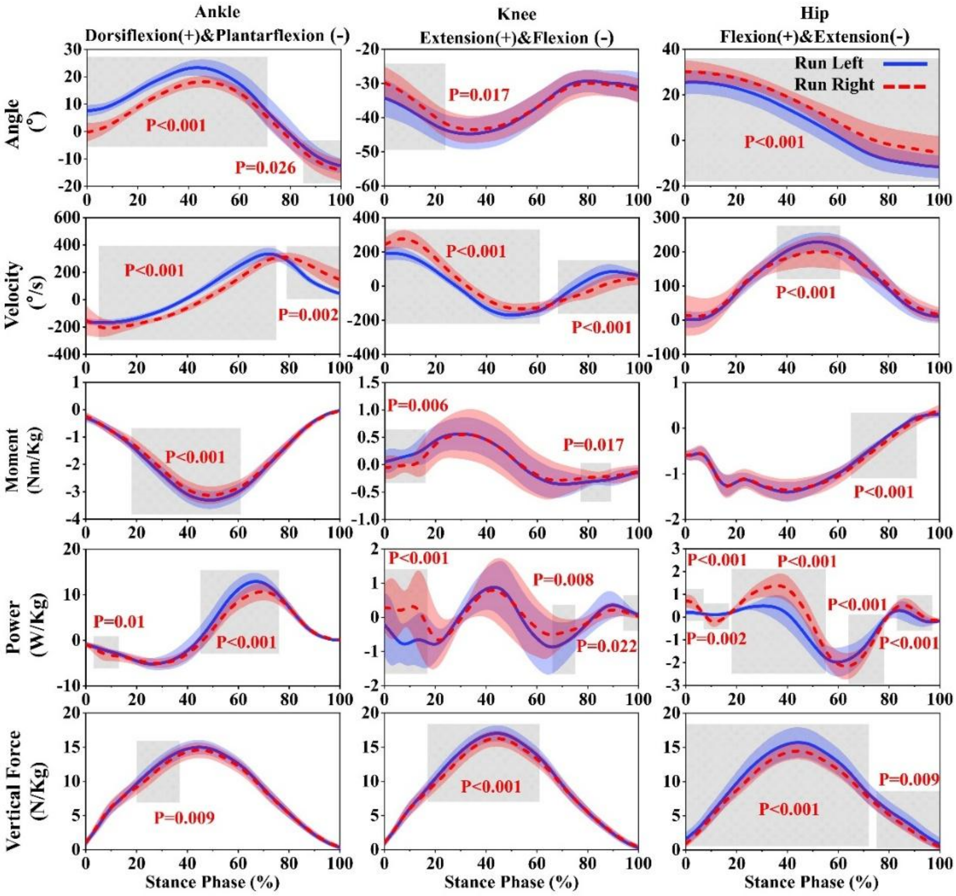


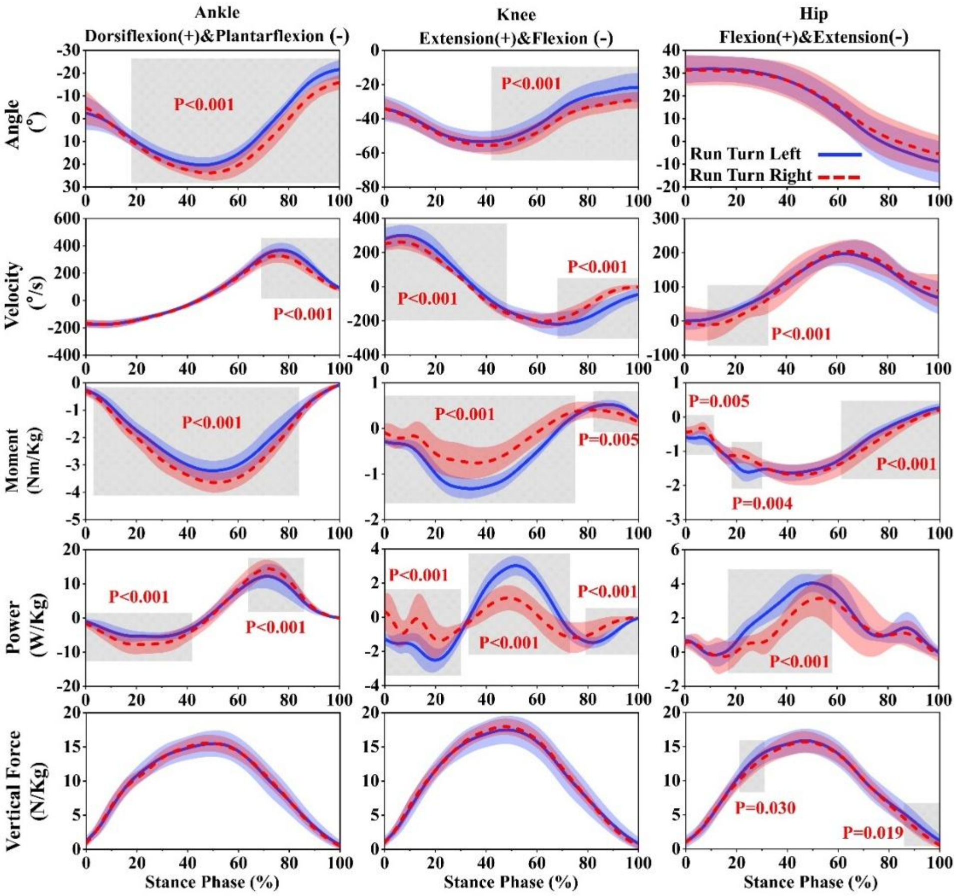
Related articles to the 2nd thesis point:

1. **<u>Liu, W.,</u>** Mei, Q., Yu, P., Gao, Z., Hu, Q., Fekete, G., István, B., & Gu, Y. (2022). Biomechanical Characteristics of the Typically Developing Toddler Gait: A Narrative Review. Children, 9(3), 406. **IF: 2.4, Q2**
2. Yu, L., Mei, Q., **<u>Liu, W.,</u>** Gao, Z., & Sun, D. (2022). Understanding Foot Loading and Balance Behavior of Children with Motor Sensory Processing Disorder. Children, 9(3), 379. **IF: 2.4, Q2**

3rd Thesis point:

In healthy adolescent athletes, inter-limb biomechanical asymmetry is widespread at the joint level and is further amplified by turning, reflecting functional limb roles rather than a simple deficit. Inter-limb asymmetry persists in healthy adolescent athletes and becomes more extensive when tasks require rapid deceleration and redirection. Time-series SPM of combined motion capture and force plate data shows broad stance-phase differences even in straight running (Figure 3.20): the right ankle angle differs from the left for 0–71% and 85–100% of stance (p<0.001 early; p<0.026 late), the right knee angle differs at 0–24% (p<0.017), and the hip angle differs across 0–100% (p<0.001). Cutting while running magnifies these effects, consistent with inside–outside limb role separation (Figure 3.21). During turning-run, the ankle angle differs for ~18–100% (p<0.001) and the knee angle for ~42–100% (p<0.001), while joint moments and powers diverge over large intervals (e.g., ankle moment ~3–84% and knee moment ~0–75%, both p<0.001). Turning while walking also shows near-whole-stance differences, including knee moment asymmetry for ~0–98% (p<0.001; Figure 3.23). These results indicate that asymmetry should be interpreted relative to task context and functional roles, rather than treated as an inherent deficit.




Ankle
Dorsiflexion(+)&Plantarflexion (-)
Knee
Extension(+)&Flexion (-)
Hip
Flexion(+)&Extension(-)
Angle (°)
Velocity (°/s)
Moment (Nm/Kg)
Power (W/Kg)
Vertical Force (N/Kg)
Stance Phase (%)
Run Turn Left
Run Turn Right
P<0.001
P<0.001
P<0.001
P<0.001
P<0.001
P<0.001
P<0.001
P<0.001
P<0.005
P=0.005
P=0.004
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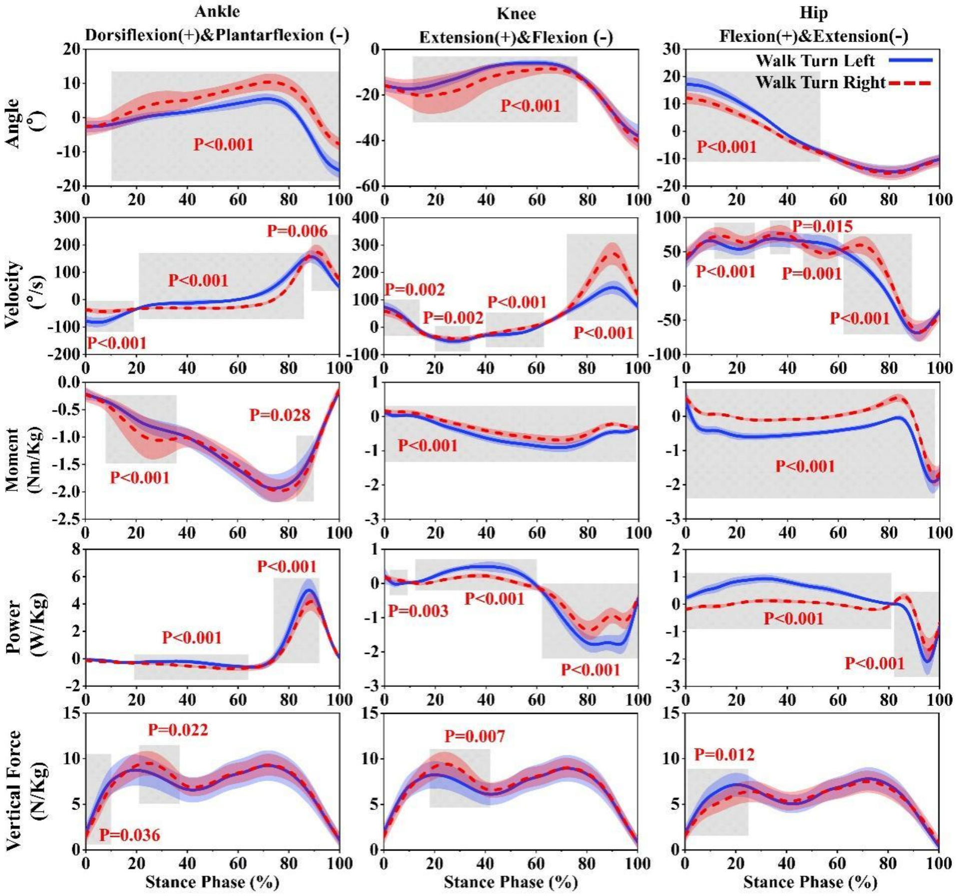
P=0.019


Ankle
Dorsiflexion(+)&Plantarflexion (-)
Knee
Extension(+)&Flexion (-)
Hip
Flexion(+)&Extension(-)
Walk Turn Left
Walk Turn Right
Angle (°)
Velocity (°/s)
Moment (Nm/Kg)
Power (W/Kg)
Vertical Force (N/Kg)
Stance Phase (%)
P<0.001
P<0.001
P<0.001
P=0.006
P<0.001
P<0.001
P=0.002
P=0.002
P<0.001
P<0.001
P=0.015
P<0.001
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P=0.028
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P=0.003
P<0.001
P<0.001
P<0.001
P<0.001
P=0.022
P=0.036
P=0.007
P=0.012

Related articles to the 3rd thesis point:

1. **Wei Liu.,** Liu Xu., Haidan Wu., Yile Wang., Hanhui Jiang., Zixiang Gao., Endre Jánosi., Gusztav Fekete., Qichang Mei. & Gu, Y. (2025). Bilateral Asymmetries of Plantar Pressure and Foot Balance During Walking, Running, and Turning Gait in Typically Developing Children. Bioengineering, 12, 151, **IF=3.8, Q3**
2. Yu, L., Yu, PM., **Wei Liu.,** Gao, ZX., Sun, D., Mei, QC., Femandez, J., & Gu, Y. (2022) Understanding Foot Loading and Balance Behavior of Children with Motor Sensory Processing Disorder. Children-Basel, 9, 379, **IF=2.835, Q2**

List of publications

Referred articles related to this thesis:

1. **Wei Liu.,** Liu Xu., Haidan Wu., Yile Wang., Hanhui Jiang., Zixiang Gao., Endre Jánosi., Gusztav Fekete., Qichang Mei. & Gu, Y. (2025). Bilateral Asymmetries of Plantar Pressure and Foot Balance During Walking, Running, and Turning Gait in Typically Developing Children. Bioengineering, 12, 151, **IF=3.8, Q3**
2. **Wei Liu.,** Mei, QC., Yu, PM., Gao, ZX., Hu, QL., Fekete, G., Istvan, B., & Gu, Y. (2022). Biomechanical Characteristics of the Typically Developing Toddler Foot : A Narrative Review. Children-Basel, 9, 406. **IF=2.835, Q2**
3. Yu, L., Yu, PM., **Wei Liu.,** Gao, ZX., Sun, D., Mei, QC., Femandez, J., & Gu, Y. (2022) Understanding Foot Loading and Balance Behavior of Children with Motor Sensory Processing Disorder. Children-Basel, 9, 379, **IF=2.835, Q2**

International conference abstracts related to this thesis:

1. **Wei Liu.,** Zhenghui LU., Xin LI., Zixiang GAO., Yining XU., Qichang MEI., Gusztáv FEKETE., Yaodong Gu. Biomechanical Analysis of Gymnastics Movements Using Wearable Motion Capture Systems and Linear Sensors: A Case Study of the Kipping Bar Muscle-Up. 7th International Conference on Material Strength and Applied Mechanics (MSAM), Győr, Hungary. 2024

Other publications:

1. Caiting Zhang., Yang Song*., Qiaolin Zhang., Ee-Chon Teo., & **Wei Liu.***. (2024). Biomechanical Study of Symmetric Bending and Lifting Behavior in Weightlifter with Lumbar L4-L5 Disc Herniation and Physiological Straightening Using Finite Element Simulation. Bioengineering, 11, 825, **IF=3.8, Q3**
2. Chengyuan Zhu, Yang Song, Yufan Xu, Aojie Zhu, Julien S. Baker, **Wei Liu.*** & Yaodong Gu*. (2024). Toe box shape of running shoes affects in-shoe foot displacement and deformation a randomized crossover study. Bioengineering, 11, 457, **IF=3.8 , Q3**
3. Enze Shao., Qichang Mei., Julien S. Baker., István Bíró., **Wei Liu.*,** & Yaodong Gu*. (2023). The effects of non-Newtonian fluid material midsole footwear on tibial shock acceleration and attenuation-Correspondence. Frontiers in Bioengineering and

Biotechnology, 1276864, **IF=6.064, Q1**

4. Enze Shao., Qichang Mei., Tongjun Ye., Bálint Kovács., Julien S. Baker., **Wei Liu.*,** & Yaodong Gu*. (2023). 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, 13, 6760, **IF=2.838, Q2**
5. Yuan Wang., Hanhui Jiang., Lin Yu1.,* Zixiang Gao., **Wei Liu.,** Qichang Mei.,* & Yaodong Gu. (2023). Understanding the Role of Children Footwear on Children Feet and Gait Development: A Systematic Scoping Review. Healthcare, 11(10), 1418, **IF=2.4, Q2**
6. Yu, L., Mei, QC., Xiang, LL., **Wei Liu.,** Mohamad, NI., Istvan, B., Femandez, J., & Gu, Y. (2021). Pricipal Component Analysis of the Running Ground Reaction Forces with Different Speeds. Frontiers in Bioengineering and Biotechnology, 629809, **IF=6.064, Q1**

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