

Wearable Inertial Measurement Units for Gait Assessment in Children with Cerebral Palsy: Current Applications, Measurement Properties, and Clinical Perspectives

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Abstract: Cerebral palsy (CP) comprises a heterogeneous group of permanent disorders of movement and posture. In ambulant children, gait may be affected by impaired selective motor control, weakness, altered muscle tone, and secondary musculoskeletal changes. Three-dimensional gait analysis remains the most comprehensive approach to instrumented assessment, but its cost, space requirements, and dependence on specialized personnel restrict routine and repeated use. Wearable inertial measurement units (IMUs) provide segmental acceleration and angular-velocity signals from which spatiotemporal, kinematic, symmetry, variability, and stability measures can be derived. This narrative review summarizes the principles, sensor configurations, gait outcomes, measurement properties, and clinical applications of IMUs in children with CP. Current evidence is strongest for spatiotemporal measures obtained from foot- or lower-limb-mounted sensors and for trunk-based measures of gait rhythm and postural control. Multisensor systems can provide additional segmental information, although accuracy depends on sensor placement, calibration, gait pattern, walking aid use, and the algorithm used to identify gait events. Laboratory and daily-life measurements should not be treated as interchangeable because they represent different aspects of walking capacity and performance. IMUs are therefore best considered a complement to clinical examination and three-dimensional gait analysis rather than a direct replacement. Future work should prioritize pediatric-specific validation, transparent algorithms, standardized reporting, and clinically interpretable thresholds across age groups and Gross Motor Function Classification System levels.

Keywords: Cerebral Palsy; Children; Gait Analysis; Inertial Measurement Unit; Wearable Sensors; Rehabilitation

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1. Introduction

Cerebral palsy is defined by permanent disorders of movement and posture caused by non-progressive disturbances in the developing brain^[1,2]. The neurological lesion is static, but its motor and musculoskeletal consequences change with growth. In ambulant children, gait deviations arise from interacting impairments rather than from a single abnormality. Reduced selective motor control, weakness, spasticity, altered muscle-tendon properties, and skeletal deformity may affect support, progression, balance, and energy expenditure^[2,3]. The clinical expression is correspondingly diverse: two children at the same functional level may adopt different combinations of equinus, stiff-knee, crouch, rotational, and compensatory trunk patterns. Instrumented gait analysis helps separate these components and supports treatment planning, particularly when clinical

observation cannot determine whether a visible deviation is primary or compensatory^[4]. Optical three-dimensional gait analysis provides detailed kinematic and kinetic information and remains the reference method for complex decision-making. Its use, however, is concentrated in specialized laboratories. Marker placement, calibration, lengthy acquisition, and post-processing also make frequent reassessment difficult, while a short, supervised walk may not represent habitual mobility. Wearable IMUs provide a complementary measurement strategy. They are portable, minimally interfere with movement, support repeated testing, and can record walking outside the laboratory^[5-7]. These properties are useful in pediatric assessment but do not establish clinical validity. Algorithms developed in adults with regular gait may perform poorly in children with atypical timing, short steps, marked asymmetry, or walking-aid use.

2. Technical Basis and Assessment Protocols

2.1 Signals and Derived Variables

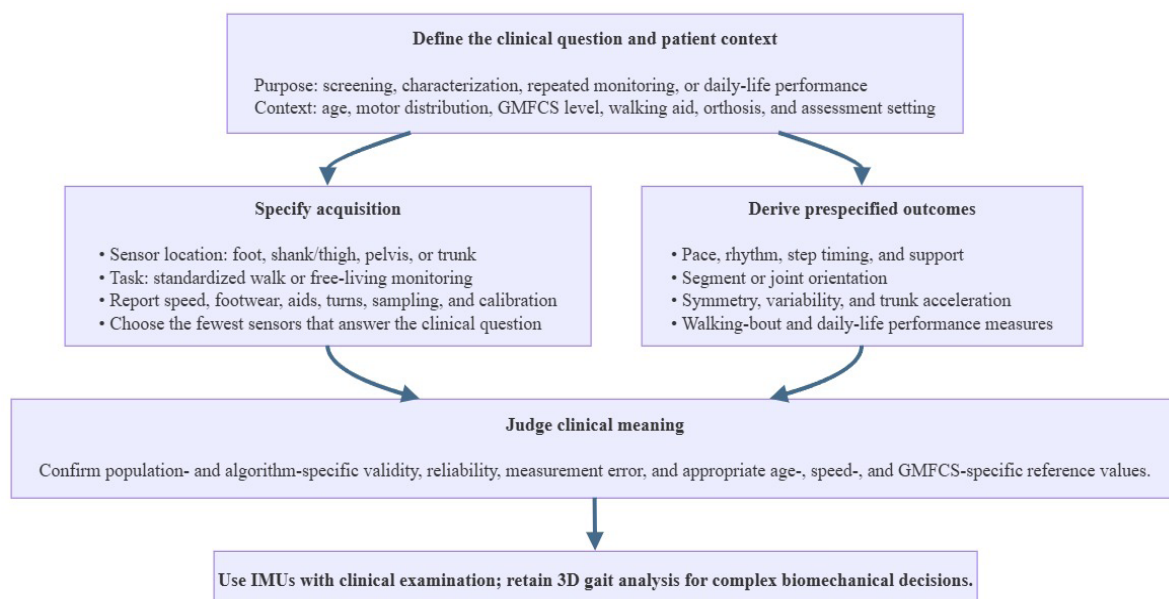
An IMU usually combines a tri-axial accelerometer and gyroscope; many systems also include a magnetometer. Accelerometers measure linear acceleration, including the gravitational component, whereas gyroscopes measure angular velocity. Magnetometers can contribute to heading estimation but are vulnerable to local magnetic disturbance. Sensor-fusion algorithms integrate these signals to estimate orientation and reduce drift^[5-7]. Because joint angles are not measured directly, their accuracy depends on sensor-to-segment alignment, anatomical calibration, integration procedures, and assumptions about segment motion.

The complexity of the output depends on the configuration. A single trunk sensor can estimate cadence, temporal regularity, acceleration magnitude, and selected stability measures. Foot-mounted sensors are well suited to detecting initial contact and toe-off and can estimate stride length, speed, strike angle, and lift-off angle. Sensors on the shanks and thighs provide additional information for gait-event detection and segmental kinematics, while multisensor systems can estimate lower-limb joint motion or describe the transmission of acceleration from the pelvis to the sternum and head^[8-13]. More sensors increase biomechanical detail but also increase setup time, calibration demands, and opportunities for placement error.

2.2 Sensor Placement and Walking Tasks

Sensor placement should be selected from the clinical question rather than from device availability alone. Foot sensors are appropriate when the primary outcomes are gait events, step timing, stride length, and ankle-foot orientation. A lumbar or pelvic sensor is useful for rhythm, trunk acceleration, and ambulatory monitoring. Lower-limb multisensor configurations are preferable when pathological gait makes foot-event detection difficult or when segmental kinematics are required. In children with greater gait impairment, a configuration combining shank and thigh sensors has shown greater robustness than simpler configurations^[10].

Figure 1: Clinical workflow for selecting and interpreting IMU-based gait measures in children with cerebral palsy



Protocol design is equally important. Short straight-path tests are efficient, but acceleration, deceleration, and turning may account for a substantial proportion of the recording in young children. Longer timed walking tests provide more strides, although fatigue and attention may affect performance. Walking speed should be recorded because many IMU-derived outcomes are speed dependent. Reports should also specify footwear, orthoses, walking aids, path length, number of trials, turning procedure, sampling frequency, calibration, gait-cycle inclusion criteria, and whether bilateral or averaged values were analyzed. These details are necessary for meaningful comparison across systems and studies. Figure 1 summarizes a practical sequence for selecting and interpreting IMU-based gait measures in children with CP.

3. IMU-Derived Gait Outcomes

3.1 Pace, Rhythm, and Support

Spatiotemporal parameters are the most established IMU outcomes in pediatric gait assessment. Common variables include speed, cadence, stride and step length, stride time, stance and swing duration, and double-support time. Foot-worn sensors have demonstrated useful agreement with optical motion capture for independently walking children with CP, including estimates of stride length, speed, and foot-contact angles^[8]. These measurements can quantify slower progression, shorter strides, prolonged support, and increased stride-to-stride variability, but their clinical meaning depends on age, body size, functional level, and self-selected speed.

Temporal averages should not be interpreted in isolation. A child may maintain mean speed by increasing cadence while taking shorter steps, and similar mean values can coexist with different levels of asymmetry or variability. Bilateral reporting is therefore important in unilateral CP. In bilateral CP, side-to-side symmetry may appear relatively preserved even when both limbs are abnormal, so comparison with age-matched reference data and other domains remains necessary.

3.2 Kinematic Measures

Kinematic estimation extends IMU assessment beyond basic timing. Foot orientation at initial contact and toe-off can provide clinically relevant information about heel contact, equinus, and progression through terminal stance. Shank, thigh, and pelvic sensors may be combined to estimate sagittal-plane joint motion. However, the agreement of IMU-derived joint angles with optical motion capture is generally less consistent than that of spatiotemporal outcomes, particularly in the frontal and transverse planes^[6, 7]. Soft-tissue motion, inaccurate anatomical alignment, and magnetic disturbance further affect estimates. Consequently, IMU joint angles should not be assumed to be interchangeable with laboratory kinematics unless the specific device, algorithm, population, and task have been validated.

A recent machine-learning study used pediatric IMU data to estimate joint kinematics and kinetics from a reduced number of sensors^[14]. It demonstrated technical feasibility, but personalized models outperformed generalized models in that sample. This distinction is important in CP, where gait patterns are more heterogeneous than in typically developing samples. Findings obtained only in typically developing children should not be generalized directly to pathological gait.

3.3 Symmetry, Variability, and Postural Control

IMUs can also describe gait quality through symmetry, variability, regularity, and acceleration-based stability measures. A trunk sensor captures the combined effect of lower-limb movement and postural control rather than a single-joint impairment. Trunk acceleration may therefore be clinically informative, but it should not be interpreted as a direct measure of balance without validation. In children with CP, trunk-worn accelerometers have identified altered regularity and acceleration patterns, while multilevel sensors placed at the pelvis, sternum, and head have shown impaired attenuation of acceleration through the upper body^[9, 12]. These findings support assessment of the trunk as part of gait, particularly when lower-limb impairments are accompanied by compensatory upper-body movement.

Upper-limb IMU outcomes, including arm-swing amplitude and asymmetry, may help characterize whole-body coordination. However, evidence specific to pediatric CP remains sparse. Observed abnormalities may reflect upper-limb impairment, adaptation to walking speed, compensatory balance strategies, or a combination of these factors. Upper-limb outcomes should therefore be interpreted together with trunk and lower-limb measures rather than as independent markers of gait severity.

3.4 Laboratory Capacity and Daily-Life Performance

Wearable sensing can measure gait outside the laboratory, but supervised and free-living recordings address different

constructs. A standardized test primarily estimates walking capacity under controlled conditions; daily-life monitoring reflects performance across variable surfaces, destinations, distractions, and bout lengths. In one study, children with CP and typically developing children wore five sensors during laboratory testing and three days of daily-life monitoring. Several gait characteristics differed between settings, although laboratory and daily-life values were correlated for some domains in the CP group. These findings support treating laboratory and free-living measures as complementary rather than interchangeable. Bout definition is a major analytical issue in daily-life monitoring. Algorithms perform more reliably during sustained walking than during very short episodes, and errors may increase in children at GMFCS levels II-III or in those using walking aids^[13]. Comparisons between clinic and daily life should match bout duration or distance where possible. Step counts alone are insufficient when the objective is gait quality; they should be combined with rhythm, pace, variability, or stability outcomes that have been validated for the intended population.

4. Measurement Properties and Clinical Use

4.1 Validity, Reliability, and Responsiveness

Validity is parameter specific. Strong agreement for stride time or cadence does not establish validity for joint angles, asymmetry, or stability indices. The reference method should match the target variable: optical motion capture for segmental kinematics, instrumented walkways or force platforms for gait events, and synchronized video or direct observation for activity and locomotion classification. Correlation alone is insufficient because two methods may correlate despite systematic disagreement; agreement statistics and measurement error should also be reported.

Pediatric studies support the feasibility of foot-, trunk-, and lower-limb-mounted sensors, but performance varies by gait pattern and functional level^[8, 10, 13]. Single-day reliability has also been examined in children with CP^[15], but reliability over one day does not establish stability across weeks or treatment periods. Responsiveness is less well studied. A post-treatment change is clinically interpretable only when it exceeds measurement error and the selected outcome is relevant to the treatment target. Minimal detectable change and minimal clinically important difference values remain unavailable for many IMU-derived pediatric gait measures.

4.2 Role in Clinical Decision-Making

IMUs can add objective information to clinical examination, functional classification, and observational gait analysis. Current clinical uses include standardized documentation of spatiotemporal gait, bilateral comparison, repeated monitoring, and assessment where full three-dimensional gait analysis is unavailable. IMUs may also quantify change after orthotic, pharmacological, surgical, or rehabilitation interventions, provided that the selected parameter is relevant to the treatment target and has acceptable measurement properties.

IMUs are not a substitute for three-dimensional gait analysis when treatment decisions require joint kinetics, detailed multiplanar kinematics, or differentiation of primary and compensatory deviations. In practice, clinical examination and functional measures define the problem, IMUs provide rapid and repeatable quantitative measures, and three-dimensional gait analysis addresses complex biomechanical questions. The quality and limitations of available validation studies, and their clinical interpretation. Representative pediatric studies are summarized in Table 1.

Table 1 Representative evidence on wearable IMUs in pediatric gait assessment

Study	Population and configuration	Contribution	Interpretive caution
Brégou Bourgeois et al., 2014 ^[8]	14 children with CP and 15 controls; foot-worn sensors	Validated selected spatiotemporal and foot-orientation measures against optical motion capture	Restricted to independently walking children
Summa et al., 2016 ^[9]	20 children with CP and 20 controls; pelvis, sternum, and head sensors	Characterized upper-body acceleration and attenuation during a 10-m walk	Upper-body acceleration is not a direct substitute for clinical balance assessment
Carcreff et al., 2018 ^[10]	Children with CP and controls; foot, shank, and thigh configurations	Showed that optimal configuration depends on functional impairment	Simpler configurations were less robust in higher GMFCS levels

Study	Population and configuration	Contribution	Interpretive caution
Paraschiv-Ionescu et al., 2019 ^[13]	15 children with CP and 11 controls; trunk-based algorithm validated in daily-life-like tasks	Supported locomotion and cadence detection across atypical gait patterns	Errors increased in more impaired gait and short walking bouts
Mohammadi Moghadam et al., 2024 ^[14]	Typically developing children; reduced IMU configurations with machine learning	Demonstrated feasibility of predicting pediatric joint kinematics and kinetics	Not a CP validation study; generalized models were less accurate
Pang et al., 2025 ^[15]	Children with CP; exoskeleton-mounted IMU data and deep learning	Explored automated gait-phase recognition	Proof-of-concept findings require external clinical validation
Bavan et al., 2026 ^[16]	Systematic review of 45 pediatric studies	Mapped sensor configurations, outcomes, and clinical readiness	Marked methodological heterogeneity remained

5. Current Limitations

5.1 Population and Protocol Heterogeneity

The CP literature includes small samples with wide ranges of age, motor distribution, movement disorder, and GMFCS level. Results from independently walking children cannot be assumed to apply to those who require aids or physical assistance. Growth adds further variation because limb length, cadence, balance strategy, and motor control change across childhood. Studies should report age-stratified results where possible and should avoid treating typically developing children as a single normative group across broad age ranges.

5.2 Technical and Analytical Limitations

Sensor displacement, inconsistent alignment, gyroscope drift, magnetic interference, soft-tissue artifact, and proprietary processing all affect reproducibility. Algorithms are often trained on small or homogeneous datasets, and accuracy may decline when applied to unfamiliar pathological patterns. Studies should report raw sensor specifications, calibration procedures, filtering, gait-event definitions, missing-data handling, and model-validation methods. For machine-learning models, participant-level separation of training and test data is essential to prevent optimistic estimates caused by data leakage.

5.3 Clinical Interpretation and Governance

Generating many variables does not necessarily improve clinical decisions. Outcomes should be selected a priori and linked to a specific impairment or activity limitation. Interpretation requires reference values stratified by age, walking speed, and GMFCS level, together with thresholds that distinguish measurement error from meaningful change. For free-living monitoring, parental consent, age-appropriate assent, data minimization, secure storage, and clear access limits are necessary because prolonged movement recordings may reveal daily routines and locations.

6. Future Directions

Future research should move from proof-of-concept studies toward clinically reproducible protocols. Priorities include multicenter validation across age and GMFCS strata, direct comparison of sensor configurations, reporting of measurement error, and development of pediatric reference datasets. Studies should determine whether multidomain profiles combining pace, rhythm, support, variability, stability, ankle-foot orientation, and upper-body movement improve clinical interpretation beyond isolated variables.

Artificial intelligence may improve gait-event detection, phenotype classification, and estimation of joint motion from fewer sensors. Deep-learning models have been explored for gait-phase recognition in children with CP ^[15]. Their clinical value, however, depends on external validation, transparent performance reporting, and robustness across devices and gait patterns. Personalized models may improve accuracy but require calibration data and may reduce scalability. The appropriate balance between personalization and generalizability remains unresolved.

A recent pediatric systematic review found considerable variation in sensor configurations, analytical methods, and reported

outcomes, limiting readiness for routine clinical implementation^[16]. Future studies should therefore prioritize reproducible measures with clear clinical interpretation rather than adding further unvalidated metrics.

7. Conclusion

Wearable IMUs can extend gait assessment in children with CP by providing portable, repeatable, and potentially real-world measurements. The evidence is most mature for spatiotemporal parameters and selected trunk-based outcomes; detailed joint kinematics, upper-limb measures, and automated classifications require further population-specific validation. Sensor configuration and analytical method should be chosen according to the clinical question and the child's functional level. At present, IMUs should complement rather than replace clinical examination and three-dimensional gait analysis. Standardized protocols, transparent algorithms, and clinically meaningful reference values are necessary before widespread routine adoption.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., et al. (2007). A report: The definition and classification of cerebral palsy April 2006. *Developmental Medicine & Child Neurology Supplement*, 109, 8–14. <https://doi.org/10.1111/j.1469-8749.2007.tb12610.x>
- [2] Graham, H. K., Rosenbaum, P., Paneth, N., Dan, B., Lin, J. P., Damiano, D. L., et al. (2016). Cerebral palsy. *Nature Reviews Disease Primers*, 2, 15082. <https://doi.org/10.1038/nrdp.2015.82>
- [3] Zhou, J., Butler, E. E., & Rose, J. (2017). Neurologic correlates of gait abnormalities in cerebral palsy: Implications for treatment. *Frontiers in Human Neuroscience*, 11, 103.
- [4] Baker, R., Esquenazi, A., Benedetti, M. G., & Desloovere, K. (2016). Gait analysis: Clinical facts. *European Journal of Physical and Rehabilitation Medicine*, 52(4), 560–574.
- [5] Iosa, M., Picerno, P., Paolucci, S., & Morone, G. (2016). Wearable inertial sensors for human movement analysis. *Expert Review of Medical Devices*, 13(7), 641–659.
- [6] Picerno, P. (2017). 25 years of lower limb joint kinematics by using inertial and magnetic sensors: A review of methodological approaches. *Gait & Posture*, 51, 239–246.
- [7] Vienne, A., Barrois, R. P., Buffat, S., Ricard, D., & Vidal, P.-P. (2017). Inertial sensors to assess gait quality in patients with neurological disorders: A systematic review of technical and analytical challenges. *Frontiers in Psychology*, 8, 817.
- [8] Bourgeois, A. B., Mariani, B., Aminian, K., Zambelli, P., & Newman, C. (2014). Spatio-temporal gait analysis in children with cerebral palsy using foot-worn inertial sensors. *Gait & Posture*, 39(1), 436–442.
- [9] Summa, A., Vannozzi, G., Bergamini, E., Iosa, M., Morelli, D., & Cappozzo, A. (2016). Multilevel upper body movement control during gait in children with cerebral palsy. *PLOS ONE*, 11(3), e0151792.
- [10] Carcreff, L., Gerber, C. N., Paraschiv-Ionescu, A., De Coulon, G., Newman, C. J., Armand, S., et al. (2018). What is the best configuration of wearable sensors to measure spatiotemporal gait parameters in children with cerebral palsy? *Sensors*, 18(2), 394.
- [11] Chen, X., Liao, S., Cao, S., Wu, D., & Zhang, X. (2017). An acceleration-based gait assessment method for children with cerebral palsy. *Sensors*, 17(5), 1002.
- [12] Iosa, M., de Sanctis, M., Summa, A., Bergamini, E., Morelli, D., & Vannozzi, G. (2018). Usefulness of magnetoinertial wearable devices in neurorehabilitation of children with cerebral palsy. *Applied Bionics and Biomechanics*, 2018, 5405680.
- [13] Paraschiv-Ionescu, A., Newman, C. J., Carcreff, L., Gerber, C. N., Armand, S., & Aminian, K. (2019). Locomotion and cadence detection using a single trunk-fixed accelerometer: Validity for children with cerebral palsy in daily life-like

conditions. *Journal of Neuroengineering and Rehabilitation*, 16(1), 24.

- [14] Mohammadi Moghadam, S., Ortega Auriol, P., Yeung, T., & Choisne, J. (2024). 3D gait analysis in children using wearable sensors: Feasibility of predicting joint kinematics and kinetics with personalized machine learning models and inertial measurement units. *Frontiers in Bioengineering and Biotechnology*, 12, 1372669.
- [15] Pang, Z., Li, Z., Li, Y., Hu, B., Wang, Q., Yu, H., et al. (2025). Gait phase recognition of children with cerebral palsy via deep learning based on IMU data from a soft ankle exoskeleton. *Frontiers in Bioengineering and Biotechnology*, 13.
- [16] Bavan, L., Ng, K., Gardner, R., Andrysek, J., & Narayanan, U. G. (2026). Wearable inertial sensors for paediatric gait assessment: A systematic review. *Gait & Posture*, 128, 110188.