Discriminating Hip and Spine Pathology based on Full-Body Movement Quality Analysis During Gait

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Intro: Conditions affecting the spine and hip affect millions globally, creating complex biomechanical dysfunction where musculoskeletal disorders trigger compensatory patterns throughout the kinetic chain. Patients presenting to orthopedic hip and spine clinics often exhibit overlapping symptoms and interconnected movement dysfunctions that extend beyond the primary affected joint. Current clinical assessment relies heavily on subjective measures (ODI, VAS) and traditional imaging that fail to capture functional movement dysfunction. However, a fundamental limitation persists conventional imaging is static and pain-insensitive, failing to capture the dynamic differences in functional dysfunction driven by pain across hip and spine pathologies. Walking represents an ideal quantitative window into neuromuscular compensation, integrating spinal stability and hip function in a measurable task. Previous studies demonstrate patients with hip or spine pathology exhibit distinct gait alterations including reduced walking speed (15-25% reduction) and altered joint coordination patterns. Traditional marker-based gait analysis, while accurate, presents significant clinical barriers including setup complexity, cost constraints, and patient discomfort. Recent advances in markerless motion capture technology offer promising solutions, with validation studies demonstrating excellent reliability (ICC 0.507-0.936) comparable to marker-based systems. For this study, we calculated a Kinematic Deviation Index (KDI) from the temporal 3D motion data of the gait analysis, capturing movement quality from the patient trajectories relative to age-matched controls. By leveraging full patient-specific gait trajectories, KDI integrates motion from all joints over time to quantify distributed movement dysfunction different groups of patients.

Methods: This study was approved by the Institutional Review Board, and written informed consent was obtained from all participants. Thirty-three participants were recruited, comprising 15 healthy controls (age: 37.7±14.6 years 9 Males, 6 Females) and 18 individuals with hip and/or spine pathology (age: 57.5±19.1 years, 9 Males, 9 Females). Participants with pathology were stratified into three diagnostic groups: isolated hip pathology (n=7), isolated spine pathology (n=5), and combined hip-spine pathology (n=6). Patients were recorded while walking at the clinic and Metrabs a convolutional neural network-based pose estimation system with automatic human keypoint localization was used for markerless joint tracking. Three-dimensional kinematic data were captured at 30 Hz across multiple gait cycles per session. Principal component analysis was performed on bilateral joint trajectories of the spinebase, spinemid, hips, knees, ankles and feet, yielding 10 anatomical landmarks. The Kinematic Deviation Index was calculated as the Mahalanobis distance between individual patient trajectories and the centroid of the control population in the reduced principal component space. Higher KDI values indicate greater deviation from normal movement patterns. Statistical comparisons used independent t-tests with Welch's correction, with significance set at $p<0.05$. Effect sizes were calculated using Cohen's d.

Results: Among 33 subjects (15 controls, 18 patients with hip and/or spine pathology), patients demonstrated 2.4-fold higher KDI scores compared to controls (132.4±28.4 vs 55.6±24.8, $p<0.001$, Cohen's d=2.87). Principal component analysis identified six components explaining 99.7% of variance (PC1: 52.5%, PC2: 28.4%, PC3: 17.5%). Ankle/foot markers contributed most heavily to PC1 (left foot: 0.562, right ankle: 0.558, right knee: 0.557). Variability analysis showed ankle joints had coefficient of variation of 104.5% compared to hip (8.1%), knee (4.4%), spine (7.6%), and foot (0.8%). Patient subgroups showed: spine-only patients (n=5, KDI: 157.6±37.8, walking speed: 0.87±0.27 m/s), hip-only patients (n=7, KDI: 120.6±21.3, walking speed: 0.46 m/s), and combined pathology patients (n=6, KDI: 125.3±12.4, walking speed: 0.41 m/s). Although walking speed differed significantly between groups ($p = 0.017$), KDI did not differ significantly. Ankle range of motion correlated strongest with KDI scores (left: $r=-0.510$, $p=0.005$; right: $r=-0.559$, $p=0.002$). No correlation existed between walking speed and KDI across the cohort ($r=0.226$, $p=0.366$). Within-subject reliability showed CV=17.1±12.6% across patients with multiple trials

Discussion: Our trajectory-based KDI successfully quantified movement dysfunction in regional pain patients, demonstrating excellent discriminatory ability (Cohen's d=2.87). The dominance of ankle-foot markers in PC1, despite hip/spine pathology, contradicts expectations that hip/spine pathology would primarily affect proximal joint kinematics, instead revealing that distal joints serve as primary adapters to proximal constraints. The 12-fold higher ankle variability (104.5% vs 8.1% hip) validates the regional interdependence/kinetic-chain framework: proximal impairments manifest as extreme distal variability through multiple co-existing strategies (foot placement, stiffness modulation, push-off timing) that preserve locomotor goals under pain or restriction. This variability-driven PC structure aligns with modern compensation theory where ankle joints function as the "final common pathway" for gait adaptation. The speed-dysfunction paradox in spine patients—highest KDI scores (157.6) coupled with fastest walking speeds (0.87 m/s)—suggests a "rushed compensation" pattern where increased cadence compensates for reduced stride efficiency. Hip patients' intermediate dysfunction with moderate speeds, and combined pathology patients' slowest gait with dysfunction comparable to hip-only patients, indicate distinct pathological signatures. The absence of speed-KDI correlation ($r=0.226$, $p=0.366$) demonstrates that velocity and movement quality represent independent dysfunction dimensions and validates our ability to discriminate underlying pathology based on full-body motion patterns. Notably, while walking speed differed significantly between groups ($p = 0.017$), the between-group difference in KDI did not reach the conventional threshold, though it approached significance; with increased power (larger N), KDI-based group discrimination may be detectable. The strong inverse ankle ROM-KDI relationship validates ankle function as a critical marker of compensatory capacity. These results support the development of motion-based diagnostics for hip-spine condition by identifying underlying joints contributing to biomechanical impairment.

Significance/Clinical Relevance: The KDI provides a trajectory-based method for quantifying movement dysfunction without requiring imaging, enabling objective assessment of functional impairment in clinical settings. These findings suggest that ankle/foot evaluation should be prioritized in hip-spine patients, as distal compensatory dysfunction may be more functionally relevant than proximal pathology. Our results are a first step in showing the potential for using motion pattens to diagnose which joints are pathological and contributing to biomechanical impairment.

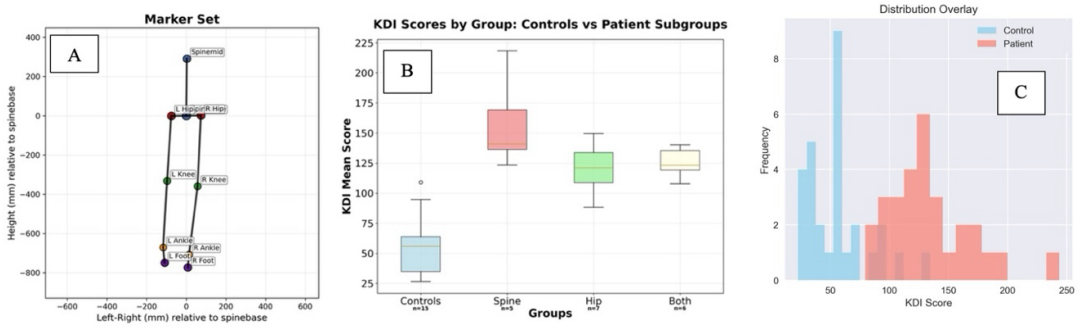

Figure A: Markers used, B: Control vs Patients KDI C: Distribution of KDI scores between controls and patients