The Effect of Chronic Low Back Pain on Whole-Body Gait Dynamics

Aniket Pratapneni[1], Girish Viraraghavan[1], Nicholas Harris[1], Pavlos Silvestros[1], Jeannie F. Bailey[1]
[1]Department of Orthopaedic Surgery, University of California San Francisco, San Francisco, CA
aniket.pratapneni@ucsf.edu

INTRODUCTION: While it is well-established that chronic low back pain (LBP) has a negative impact on gait, its mechanisms of influence on movement patterns in gait are poorly understood, making it difficult to quantify and objectively assess the severity of functional impairment in patients. Much of the prior work exploring the impact of chronic LBP on gait has utilized conventional biomechanical metrics – such as stride length or double support time – but these offer limited insight into how whole-body coordination is affected. The complex nature of human movement requires frameworks that can capture global patterns of joint interaction, not just localized deviations. We hypothesized that individuals with chronic LBP would demonstrate quantifiably different patterns of inter-joint coordination during walking, reflective of compensatory or constrained motor control strategies. To uncover these differences at two different scales, we integrated conventional spatiotemporal metrics with unsupervised dimensionality reduction and network theory-based modeling of joint synchrony.

METHODS: We analyzed treadmill walking trials from 56 adult participants (24 chronic LBP, 32 controls, 44.6% male, average age 52.3 ± 16.8), each of whom walked for up to 11 minutes at a self-selected speed while markerless motion capture data was collected every minute using an 8-camera system (THEIA3D). Each trial yielded up to 11 15-second segments (some trials were stopped early if pain worsened significantly), from which we extracted full-body joint trajectories at 180 Hz. Each trial was spatially normalized by rotating and translating into a standardized coordinate space. Gait metrics such as stride length, stride time, double support time, and joint ranges of motion (ROM) were computed for each of these segments and normalized for leg length where applicable. Gait events (heel strike and toe off) were identified via the THEIA3D system, delineating a total of 13,326 valid strides. For trajectory decomposition and analysis, each stride was time-normalized, and we performed a functional principal component analysis (fPCA) on each dimension of each joint (e.g., right ankle along the mediolateral axis). Statistically significant functional principal components (fPCs) were identified via group comparisons of fPC coefficients. To examine global coordination, we constructed joint-interaction graphs for each 15-second segment: each node represented a joint, and connections were established between joint pairs whose Pearson correlation between their 3D trajectories was greater than the population average. We then computed global and local network metrics, including mean degree, global efficiency, and clustering coefficient in order to quantify joint coordination at local and global scales of the body. Group-wise differences in these metrics were assessed using non-parametric statistics. We further visualized that average correlation between pairs of joints for patients and controls as well as the between-group differences as heatmaps.

RESULTS: Chronic LBP patients exhibited a 13.2% decrease in height-adjusted gait speed (Fig. 1. $p=0.02$, Cohen's $d=0.72$), a 5.5% increase in double support time ($p<0.01$, $d=0.47$), a 5.5% decrease in stride length ($p<0.01$, $d=0.45$), but no significant difference in stride time. Notably, however, both double support time ($r=-0.83$, $p<0.01$) and stride length ($r=0.93$, $p<0.01$) were found to be strongly correlated with height-adjusted gait speed. Furthermore, after correcting for the differences in normalized gait speed, there were no significant differences in stride length and double support time, indicating that the differences in these conventional metrics are largely attributable to the speed at which chronic LBP patients are comfortable walking. fPCA revealed multiple trajectory components with significant group differences. Effect sizes were largest ($d>0.5$) in the vertical axis trajectories of the shoulders, knees, and ankles. In all of these trajectory comparisons, patients moved with decreased amplitude of motion, indicating constrained movement, which may cause the aforementioned decrease in gait speed.
Network-based joint trajectory correlation analysis revealed that LBP patients' gait was characterized by more rigidly synchronized movement. Specifically, both global efficiency ($p<0.01$, $d=0.69$) and average clustering coefficient ($p<0.01$, $d=0.68$) were elevated in patients, indicating that patients had more tightly coordinated movement at a global, whole-body scale as well as between local clusters of joints. Patients also showed an increase in the average number of joints each joint was coordinated with ($p<0.01$, $d=0.62$), consistent with a reduction in modular movement. Heatmaps of average pairwise correlations confirmed that while intra-trunk coordination remained unchanged, trunk-leg coordination was consistently higher in patients (Fig. 2). In particular, the shoulders and spine moved in greater synchronicity with the ankles. Furthermore, no correlations were found between the conventional metrics and the network-based metrics (Pearson $r<0.2$ for all pairwise comparisons), and the differences in whole-body coordination persisted after correcting for height-adjusted gait speed, indicating that this analysis approach captured differences in motion that the conventional metrics did not.

DISCUSSION: This work highlights that movement in LBP is not simply a matter of alterations in single metrics but involves a shift in how the body coordinates its segments across time. The use of graph representations allowed us to model coordination as a property of the entire network of joints, revealing multiscale increased synchrony and reduced modularity and complexity in the gait of LBP patients. Importantly, these differences were not visible using traditional joint-angle or summary-metric analyses alone, but they offer an explanation as to the underlying changes in motion dynamics that manifest in changes like increased double support time or decreased stride length.

SIGNIFICANCE/CLINICAL RELEVANCE: These findings demonstrate that chronic LBP alters not just joint trajectories but whole-body movement patterns. Graph-based modeling and fPCA offer interpretable, quantitative frameworks that may enable more sensitive movement assessments and patient risk profiling in clinical settings.

IMAGES AND TABLES:

Fig 1: Tracking Data Visualization

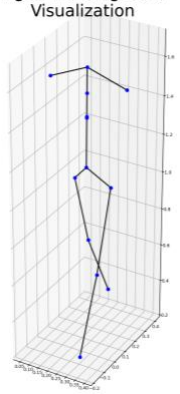

Fig 2: Height-Adjusted Speed by Group

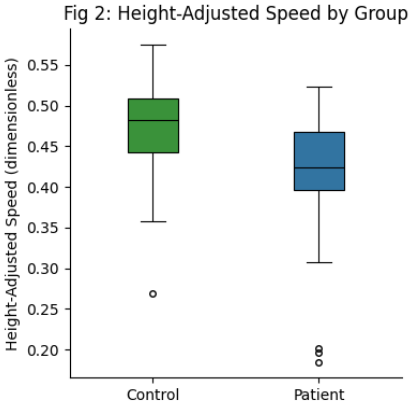

Fig 3: Inter-Joint Patient Pearson r - Control Pearson r