Improving Care for Spinal Deformity Patients: Utilizing Wearable Tools for Functional and Disability Assessments

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INTRODUCTION: Disability and functional assessments of spinal deformity are notoriously inaccurate for diagnosis and prognosis. While sophisticated motion analysis lab data has great quality lack of cost-effectiveness prohibits adoption as a standard of care (SOC). In contrast, wearables are both cost-effective and broadly available and have been incorporated into telehealth SOC for various disparate populations. As a result, telehealth has become increasingly important, and wearables are a useful adjunct for remote clinical assessments. The rapid expansion of telehealth has created a growing need for objective, noninvasive tools to assess patient function outside traditional clinical settings that do not have the same associated cost, geographic challenges, and volume constraints of traditional motion capture. Although wearable sensors are widely used to monitor general health metrics, few devices have been validated explicitly for assessing outcomes directly related to spinal impairments. Understanding patients' real-world movement patterns can help clinicians understand symptoms and recovery. Therefore, this study has 3 aims: 1. Validate the accuracy of spine-specific wearable sensor measurements by comparing them with a Gold standard motion capture system; 2. Recognize the type of activities at home in deformity patients using a segment-level motion recognition pipeline; and 3. Perform a retrospective analysis of patients' at-home data to calculate clinically relevant variables such as gait, sway, and Cone of Economy (CoE).

METHODS: Institutional review board (IRB) approval was obtained for this study. Forty-two adults with scoliosis and matched controls were recruited and fitted with inertial measurement units (IMU; Vicon), including a sensor positioned at T1 in addition to the standard full-body configuration used in laboratory-based motion capture. Participants completed a standardized battery of functional assessments and daily activities (walking, standing, lifting, sitting) recorded simultaneously by both systems. For the at-home component, only the T1-mounted IMU was worn, with activities performed twice daily over a two-day period. Then, machine learning motion recognition was developed for model training and activity pattern recognition. Raw acceleration and angular-velocity streams were windowed into overlapping segments (length 1.5 s, step 1.0 s). From each window, time-domain features (e.g., mean, variance, zero-crossings) and frequency-domain features (e.g., spectral entropy, dominant frequency) were extracted. A walking identifier RNN (Recurrent Neural Network) Layer, plus a second layer of LSTM-based RNN was trained using a 70/30 training/test split with 5- fold cross-validation. Window-level probabilities above a threshold of 0.60 were merged into continuous segments through duration-based post-processing. The segments of data identified as the activities of interest were then retrospectively analyzed using the traditional MATLAB pipelines implemented in the clinic for markered motion capture data in order to calculate clinically relevant variables, such as gait, sway, and CoE for further analysis. The spine angles collected by both methods were aligned and the similarity quantified via Intraclass Correlation Coefficient (ICC). The performance of the model was evaluated on the hold-out test set using time-weighted accuracy, segment coverage, segment precision, and mean intersection-over-union (IoU). Comparisons between cohorts were conducted using post-estimation comparisons with statistical significance for all variables set at $p < 0.05$.

RESULTS: Validation analyses demonstrated excellent agreement between IMU- and motion capture–derived spine angles for maximal ranges of motion during static balance and gait tasks (Romberg flexion/extension ICC = 0.98; walking flexion/extension ICC = 0.97). Good agreement was observed for ranges of motion across several activities (ICC = 0.75–0.88), with moderate agreement in dynamic lifting tasks (ICC = 0.65–0.74). Transitional and multiplanar movements, including sit-to-stand, showed weaker reliability (ICC < 0.65), indicating the need for refinement in complex activity detection. Clinically relevant measures such as CoE and postural sway during walking and balance tasks demonstrated strong consistency across systems. At-home activity recognition achieved an overall accuracy of 0.75, with the Random Forest model demonstrating robust performance in common activities. Standing was identified with a precision of 0.74, recall of 1.00, and F1-score of 0.85; walking with a precision of 0.79, recall of 0.99, and F1-score of 0.88. Bed- and lifting-related activities showed reliable detection (precision, recall, and F1-scores 0.55–0.73). Retrospective analysis of at-home recordings yielded clinical metrics within acceptable limits compared with marker-based motion capture, with cone of economy and maximal sway in both coronal and sagittal planes demonstrating the strongest concordance.

DISCUSSION: Wearable technologies designed specifically for spine deformities offer a practical alternative to traditional motion labs by enabling dynamic assessments of spinal alignment and function during activities of daily living. This is clinically meaningful, as surgical decision-making for adult spinal deformity increasingly prioritizes restoration of spinal balance tailored to patient-specific factors (age, pelvic morphology, sagittal harmony), yet current assessments rely almost entirely on static radiographs. Static imaging cannot capture dynamic compensations that contribute to disability or sequelae such as adjacent segment pathology. The preliminary validation of our spine-specific wearable demonstrates feasibility in collecting clinically relevant measures, including sway and cone of economy, outside the clinic. Importantly, these tools provide an opportunity to longitudinally monitor recovery and perioperative function in the patient's home environment. While detailed disability and functional analyses still require motion labs, validated wearable sensors may bridge the gap by supplying continuous, objective data that complements radiographs, PROMs, and DFOMs. Expanding the dataset and refining detection of transitional movements will further enhance accuracy. Future studies will explore perioperative monitoring to determine how specific functional changes (e.g., ease of lying down, standing tolerance, gait quality) align with radiographic outcomes and inform individualized treatment strategies.

SIGNIFICANCE/CLINICAL RELEVANCE: This study addresses a critical gap in spinal deformity care by validating a spine-specific wearable capable of capturing dynamic functional data during daily life. By enabling longitudinal, home-based monitoring of mobility and alignment, this technology provides clinically relevant insights into patient disability and recovery that complement radiographic and PROM-based assessments, potentially improving surgical planning, enhancing patient-specific treatment, and ultimately reducing healthcare costs while improving outcomes.

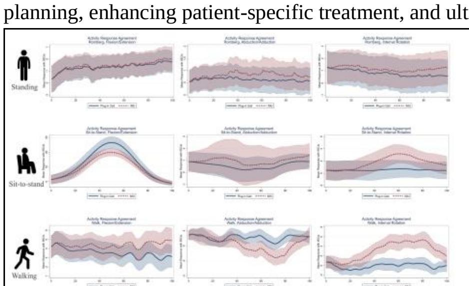

Figure 1. Representative plots demonstrating agreement between IMU-derived (red) and motion capture–derived (blue) kinematic signals during balance and gait tasks.

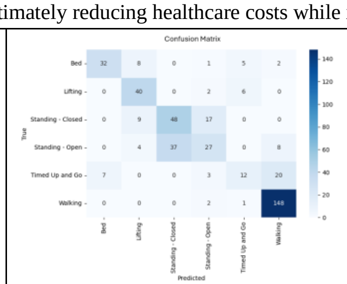

Figure 2. Confusion matrix illustrates model performance, with predicted activities mapped against ground-truth classifications.

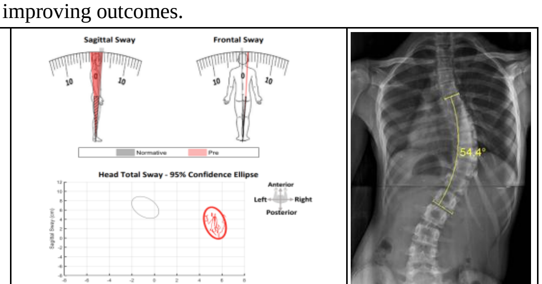

Figure 3. Wearable sensors captured balance and functional performance metrics in adult spinal deformity patients (red) and controls (gray) in the home environment.