Thesis Title Reactive Balance Strategy Identification Using Motion Capture and Unsupervised Clustering

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ABSTRACT

Balance is maintained through the continuous integration of visual, vestibular, and somatosensory inputs, translated into coordinated joint movements across the lower limb. Traditional balance assessments rely on subjective clinical observation, which limits the ability to detect complex, multi-joint strategies and hidden postural patterns. This thesis proposes an objective, data-driven framework integrating motion capture technology with unsupervised machine learning to identify balance strategies in both adult and pediatric populations.

The research was conducted in two phases. In Phase 1, the framework was developed and validated using the publicly available KINECAL adult dataset from PhysioNet. Three clustering algorithms — Agglomerative Hierarchical, Gaussian Mixture Model, and K-Means — were applied to lower-limb joint angle data, identifying three postural archetypes: Good Balance, Slight Unbalance, and Poor Balance. K-Means achieved the best performance at k=3, confirmed by the Elbow Method and Silhouette Score.

Continuously, the research was scoped down to explore the hidden balance strategies in children who experienced the Chronic Ankle Instability within the past year. In Phase 2, the framework was extended to 44 children aged 7 to 13 years-old performing the m-CTSIB under four sensory conditions, using the Xsens 17-sensor IMU system, underwent rigorous normalization and multicollinearity mitigation before being processed through four clustering algorithms: K-means, Spectral, BIRCH, and Hierarchical. The optimal four-cluster solution was validated through internal clustering metrics and PCA visualizations. Our analysis successfully delineated our

condition-specific postural archetypes: Mixed Strategy (Hip-Ankle), Ankle-Knee Strategy, and Atypical/Divergent patterns — each varying in joint amplitude and directional dominance across sensory conditions. Notably, the results revealed a sensory-dependent shift in motor control logic; while participants favored a localized Ankle Strategy during baseline and visual-deprivation tasks on stable surfaces, the removal of somatosensory cues forced a strategic shift toward a Mixed Strategy (Hip-Ankle). In the most demanding scenarios—where both visual and somatosensory inputs were compromised—the majority of children transitioned to a complex Integrated Strategy, necessitating synchronized Hip, Knee, and Ankle adjustments to maintain stability. Furthermore, the model also identified rare, atypical clusters characterized by divergent joint movement patterns — including opposite-directional responses and extreme distal amplitudes — that remain largely invisible to manual clinical observation.

To evaluate the quality and validity of clusters, this thesis proposed the new set of input features extracted from three rotational degrees of freedom (DoF) along with their joint descriptions. Cluster interpretations were further characterized through a plane-specific kinematic analysis — decomposing joint behavior across the sagittal (flexion/extension), frontal (abduction/adduction), and transverse (internal/external rotation) planes — consistent with ISB-recommended tri-planar reporting conventions. Each feature was further processed into three proposed temporal formats which are Discrete 5-second intervals (D5I), Segmented 5-second averages (S5A), and Overall trial mean (OTM). The metrics i.e. Silhouette Coefficient (SC), Calinski-Harabasz Index (CH), and Davies-Bouldin Index (DB) were used to confirm that the best clustering algorithm to identify the balance strategies in human are vary depending on different clinical scenarios.

Collectively, these findings demonstrate the testing of four different scenarios show that FiSEOTL reveals the majority of the population uses the Mixed Strategy (Hip-Ankle) by resulting of BIRCH clustering algorithm with the SC=0.420, CH=29.677, DB=0.578; while FiSECTL and FoSEOTL reveal the majority of the population use the Ankle-Knee Strategy by resulting of Spectral clustering algorithm with the SC=0.548, CH=22.759, DB=0.448 and Hierarchical Clustering with the SC=0.404, CH=28.940, DB=0.663 respectively; and the FoSECTL reveals the majority

of the population uses the Mixed Strategy (Hip, Knee, Ankle) by resulting of K-Means clustering algorithm with the SC=0.416, CH=33.812, DB=0.720.

Therefore, this thesis demonstrates that unsupervised clustering applied to motion capture data provides objective and clinically meaningful insights into balance strategy use that traditional observation-based assessment cannot offer.

Keywords: Balance Strategy, Motion Capture, Unsupervised Clustering, m-CTSIB Postural Control