Entropy Analysis of Leg Motion Pattern for Quantitative Evaluation of Gait Impairment

INTRODUCTION: In biological systems, although responses at each single factor level are reasonably deterministic (e.g., electrical signaling at a single neuron level), final responses from a combination of these deterministic factors exhibit substantial variability (i.e., defined as biological complexity), consistently with the “chaos” theory. In a concept called “the loss of complexity hypothesis [1],” healthy conditions in biological systems are characterized by high system complexity, which is reflected as an optimal state of variability [2]. In the case of musculoskeletal systems, it has been empirically well-recognized that joint disorders cause a monotonic leg motion pattern during gait (i.e., limp). Potentially, measurement of leg motion pattern variability during gait helps evaluate degrees of gait impairment.

We have developed a convenient non-invasive technique to quantify stride-to-stride variability in leg motion patterns during gait. In this technique, tri-axial acceleration time-series data of the lower limb segment (measured bilaterally) are analyzed by means of a non-linear measure “sample entropy (SampEn)” [3]. SampEn ($m, r, N$) quantifies the variability of a time-series dataset consisting of $N$ data points, by assessing the probability that equal sequences of length $m$ would remain similar after a time increment. The degree of similarity was determined by the tolerance $r$. The output was a unitless, non-negative number where higher values indicate more variable (less monotonic) motion patterns.

This study aimed to test the potential of this novel technique to identify gait impairment. We hypothesized that leg motion patterns during level walking would become more monotonic with aging, and that older adults with symptomatic knee osteoarthritis (OA) would walk with more monotonic leg motion patterns compared to age-matched asymptomatic control subjects.

METHODS: Fifty-seven subjects free from musculoskeletal symptoms (age: 21-79) and fifty-two subjects with symptomatic knee OA (age: 54-79 with Kellgren-Lawrence grade ≥2 and knee pain or stiffness on most days of the prior month) and were recruited with IRB approval. These subjects completed a long distance corridor walking. The asymptomatic (control) subjects completed two sets of a 200-meter walking (5 laps in a 20 meter walkway, one at a self-selected pace and the other at his/her fastest pace. The OA subjects were asked to walk 400 meters at the fastest pace that they could maintain for that distance (or if he/she felt unable to walk 400 meters, then to walk for 2 minutes at that fastest pace). Each walking test was timed (distance was measured for the 2 minute walk), and the average velocity was computed.

Leg motions during the walking test were measured using a lightweight wireless activity monitoring system (DigiTrac®, IM Systems Inc., Baltimore, MD), attached bilaterally just above each ankle. This device measured/recorded tri-axial accelerations of the lower leg segment, at a sampling rate of 40 Hz. The data recorded were analyzed using a custom Matlab program, to compute SampEn ($m, r$, $N$) values. The tri-axial acceleration data (Figure 1) were analyzed for every 10 second ($N = 400$) interval, with the other parameters set at typical values: $m = 2$ and $r = 0.2$.

RESULTS: In the control subjects, the self-selected pace data (Figure 2A) had a significant trend ($r = -0.287, p = 0.031$) that SampEn values gradually decreased with age, and this trend became more distinct at the fastest pace ($r = -0.420, p = 0.001$, Figure 2B). Intra-subject correlations between datasets (self-selected and fastest) were high ($r = 0.822$), while values were higher at the fastest pace (mean 128%, $p < 0.001$). SampEn values in the OA subjects were significantly lower than in the age-matched control subjects ($n = 17$), not only compared to the data at the fastest pace ($p < 0.001$), but also compared to the data at the self-selected pace ($p < 0.001$). A similar trend was found in walking velocity (Figure 3A). However, even in a comparison between velocity matched data (Figure 3B), SampEn values were significantly lower in the OA subjects ($p < 0.001$).

DISCUSSION: The data supported both hypotheses that stride-to-stride variability in leg motion pattern during gait is lower with greater age and in adults with symptomatic knee OA. Reduction of leg motion variability in knee pathology is consistent with previous observations in patello-femoral pain syndrome [4] and ACL deficiency [5]. Unfortunately, the non-smooth ‘trajectory’ characteristics of the present 3D acceleration datasets (Figure 1) imply that the current data sampling rate (40 Hz) is insufficient to evaluate small changes in walking motions, and particularly for motion analysis during running. However, even in these datasets, the trends demonstrated were very consistent with the theoretical framework that we adopted, suggesting that our approach is promising as a basis for developing a valid technique to quantify gait impairment. Furthermore, our approach does not require elaborate gait analysis equipment, lending itself to multi-institutional studies.

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References:

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