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Accelerometer-based determination of gait variability in older adults with knee osteoarthritis

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ABSTRACT

Knee osteoarthritis (KOA) can affect the spatiotemporal (ST) aspects of gait as well as the variability of select ST parameters based on standard linear measures of variability (e.g., standard deviation (SD) and coefficient of variation). Non-linear measures (e.g., fractal scaling index (FSI) and sample entropy) can be more sensitive to changes in gait variability, and have been used to quantify differences in the stride patterns of patients with Parkinson's disease and the motion of ACL-deficient knees. However, the effect of KOA on the dynamic complexity of the stride pattern has not been investigated. Therefore, the purpose of this study was to investigate the effect of KOA on gait variability (linear and non-linear measures) in a group of older adults, and to compare these results to a healthy control group. Participants walked for 10 min with a tri-axial accelerometer placed at the lower back. Mean and SDs of stride time and step time as well as the FSI for the entire series of stride times were calculated for each participant. Participants with KOA had significantly greater mean stride time ($p = 0.031$) and step time ($p = 0.024$) than control group participants. While stride and step time variability (SD) were greater in the KOA group, the differences were not significant, nor was the difference in the FSI. Low statistical power ($\beta = 0.40$ and 0.30 for stride and step time SD, respectively) combined with the confounding effects of walking speed and heterogeneous KOA severity likely prevented significant differences from being found.

1. Introduction

As individuals age, changes in gait patterns become apparent, and are often influenced by the effects of aging itself. However, knee osteoarthritis (KOA) can have an even more pronounced effect on gait alterations with a subsequent negative impact on an older adult's level of independent living. The degenerative effects of KOA have been shown to impact several of the age-related changes in the mean spatiotemporal parameters of gait (e.g., shorter stride lengths, longer stance phases, reduced speed, longer stride time and increased double support time) [1–4], which may reflect compensation strategies to minimize joint pain and protect the knee [4].

These compensations can also affect the variability of gait [5–7], and recently the subject of gait variability (i.e., the magnitude of stride-to-stride fluctuations and their changes with respect to time) has become a more thoroughly investigated aspect of gait analysis. It provides important information about the rhythmic pattern of the gait cycle that is overlooked when more traditional measures such as the average speed, mean stride time, and mean step length are determined [8]. In non-linear biological systems, variability is related to complexity, wherein a certain amount of variability in the gait cycle is considered to be healthy and represents adaptability and efficient gait control in response to unstable environmental conditions [9]. However, as people age and/or experience different pathologies, the behavioural complexity of the neuromusculoskeletal system can change. Too much or too little variability can affect the stability of the system, as has been shown by studies that have found increased values for the standard deviation (SD) of stride time [10,11].

Normal gait cycles also possess fractal properties that can be quantified using the fractal-scaling index (FSI), which provides a measure of the long-range, self-similar stride patterns that are associated with gait stability[8]. Studies show that the FSI can discriminate between healthy gait patterns and those affected by disease and aging, such that lower values (i.e., more random uncorrelated patterns of strides) are associated with impaired health [8,12,13]. More random gait patterns are often associated with rhythmic impairments in the neuromuscular control system, but the literature also indicates that increased randomness (less complexity) and gait instability are also associated with joint

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pathology [5–7]. This suggests that patients with KOA may express decreased complexity as demonstrated by lower FSI values. Although it is evident that KOA can negatively affect the basic parameters of gait compared to healthy individuals, there has been limited research on the effects of KOA on gait variability. Kiss [14] and Kiss et al. [15] have shown a relationship between KOA and increased gait variability for parameters such as step length and double-support phase duration. However, it has been suggested that different gait variability parameters represent different constructs [16], and as such additional research is needed to fully understand the gait variability characteristics that are associated with KOA. Determining the effects of KOA on stride pattern variability and the fractal structure of the gait cycle will provide a better understanding of the extent to which changes in complexity are associated with the degenerative nature of KOA. To our knowledge, the effect of KOA on stride time variability and the fractal dynamics of the gait cycle has not previously been investigated.

Therefore, the purpose of this study was to investigate the effect of KOA on gait variability (linear and non-linear measures) in a group of older adults, and to compare these results to a healthy, age- and sex-matched control group. It was hypothesized that gait variability (i.e., stride time SD and step time SD) would be greater and the pattern of strides would be more random/uncorrelated (i.e., lower stride time FSI) in the KOA group compared to the healthy older adult control group.

2. Methods

2.1. Participants

Thirty older adults (KOA: $n = 15$; Control: $n = 15$) matched for age and sex participated in the study (see Table 1). Test participants were admitted to the study if they received a medical diagnosis of KOA, were $\geq$55 years of age, and could walk for ten minutes without the use of an assistive device and without pain. All participants in the KOA group had bilateral KOA. Based on radiographic assessments of the participants' knees, the Kellgren-Lawrence (K-L) grading scale was used to categorize the severity level of KOA. Severity levels varied across participants, where five participants had a K-L grade of 4, eight had a grade of 3, and two had a grade of 2. Exclusion criteria included any recent history of surgery affecting the legs or lumbar spine, OA in any other joint of the lower extremity, any other neuromuscular disorders, history of stroke, cardiovascular disease, or any other medical condition or physical impairment that would affect their gait, balance, and/or their ability to walk at a steady pace for ten minutes. Control group participants had no limitations in terms of walking ability and were selected using the same inclusion/exclusion criteria as the KOA group, aside from the presence of KOA. The study was approved by the local research ethics board, and all participants provided written, informed consent prior to participating.

Table 1
Subject Demographics, KOOS Score, and Speed Comparisons between Groups.

Parameter	Control Group (8 Females; 7 Males) (*Mean* ± *SD*)	Knee OA Group (8 Females; 7 Males) (*Mean* ± *SD*)	*p*
Age (years)	66.07 ± 10.04	64.57 ± 6.75	0.657
Height (cm)	167.46 ± 11.02	167.18 ± 9.68	0.942
Mass (kg)	72.35 ± 17.08	85.15 ± 11.03	.021*
BMI (kg/m^2)	25.52 ± 3.75	30.57 ± 3.97	.001*
KOOS	98.67 ± 3.66	51.07 ± 14.36	.000*
Speed (m/s)	1.45 ± 0.24	1.29 ± 0.15	.032*

Note: An asterisk (*) indicates a significant difference between groups ($p < 0.05$).

2.2. Procedures

Body height and mass were measured to determine body mass index (BMI) and the Knee Injury and Osteoarthritis Outcome Score (KOOS) was administered to all participants on the day of testing. The KOOS is a reliable and valid health-status instrument to assess pain, stiffness, difficulty in activities of daily living, and difficulty with exercise and knee-related quality of life [17]. Each participant walked around an indoor 200-m oval track for ten minutes at a self-selected speed in a consistent manner. The distance walked (m) was recorded to estimate the average speed (m/s) of the entire walk. A self-selected speed was chosen to more accurately represent the typical natural gait pattern of each participant according to their stature and other physical factors such as strength and flexibility.

A tri-axial accelerometer (GENEActiv, Cambridge, UK), attached to a belt and located firmly in place on the lower back near the body's centre of mass, was used to collect acceleration data during the walking trial. The data was sampled at 100 Hz, which is consistent with sampling frequencies used by previous accelerometer-based research to determine measures of gait variability [18].

2.3. Data analysis

All data sets were reduced to nine minutes by removing the first 15 s and final 45 s of walking data to achieve accurate measurements of stride and step time variability as well as FSI. Steady-state walking speed in elderly individuals can be achieved after the first 2.5 m of walking [19], so the first 15 s of data were removed to ensure that participants had achieved a steady-state walking speed prior to the analysis. The final 45 s of data were removed to eliminate any irregularities in the participant's gait pattern that may have been associated with the termination of their walking trial. Calculating valid measurements for the fractal scaling index (FSI) has been shown to require a minimum of five minutes of walking data to allow for true testing of the long-range correlations, and improved levels of reliability have been found for trials that were eight-minutes in duration [13,20]. Generally, there is a positive relationship with the length of the walking trial and the accuracy of the FSI [8]; therefore, nine minutes of data was used to achieve accurate measurements of gait variability and FSI [21].

Custom MATLAB (MATLAB, Natick, MA) scripts were used to filter and detect the pattern of peak accelerations in the anteroposterior direction, which corresponded to the heel strikes of each foot. A zero lag, 4th order Butterworth low-pass filter with a cut-off frequency of 10 Hz was applied to the raw acceleration data. The peak negative anteroposterior acceleration values were used to compute the step and stride times for each leg throughout the walking trial [22].

The individual left and right mean step times were added together to quantify the mean stride time for each participant. The SD of step time and stride time was used to determine the level of temporal gait variability. A detrended fluctuation analysis of stride time, as described by Hausdorff et al. [8] and Kobsar et al. [22], was used to determine the FSI (α).

2.4. Statistical analysis

An independent *t*-test was used to compare the subject demographics, KOOS score and average walking speed. A second independent *t*-test was used to compare the gait variability