



Full length article

Individuals with knee osteoarthritis present increased gait pattern deviations as measured by a knee-specific gait deviation index

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ABSTRACT

Background: A biomechanical analysis can provide valuable information on osteoarthritis (OA) gait, but important multidimensional interactions are often ignored. The Gait Deviation Index (GDI) was designed to address the issue of data complexity in gait analyses by providing a single, encompassing, value for one's deviation from a normative reference group.

Research Question: The primary aim of this study was to examine differences in a knee-specific GDI among young adults, and older individuals with and without knee OA. Secondly, we aimed to examine these differences while controlling for gait speed.

Method: Sagittal and frontal plane knee joint angles and moments were used in the computation of a GDI among young adults, and older individuals with and without knee OA. The GDI was calculated such that scores $\geq 100\%$ were considered typical young-healthy gait and a 10% decrease below 100 equated to 1 standard deviation from typical gait. Scores were first examined using a one-way analysis of variance, and examined again after correcting for gait speed.

Results: The GDI was calculated for three groups: young-healthy adults ($n = 52$), older individuals without knee OA ($n = 56$), and individuals with knee OA ($n = 191$). Those with knee osteoarthritis exhibited a mean GDI of 87.2 (11.1), which was significantly lower than young adults (99.6 (10.6); $p < 0.001$) and older individuals without knee OA (94.3 (11.0); $p < 0.001$). Differences in GDI remained consistent after controlling for gait speed. Knee OA gait waveforms displayed significant variability across similar GDIs, specifically in frontal plane patterns.

Conclusion: Those with knee osteoarthritis exhibited lower (worse) GDIs compared to those without knee osteoarthritis and young, healthy individuals. After correcting for gait speed, these findings did not change. The GDI highlighted the significant variability in gait waveforms within individuals with knee OA, but the clinical utility of the GDI score itself remains limited.

1. Introduction

A biomechanical gait assessment can provide a vast amount of information on movement patterns that are vital in studying the etiology and treatment of musculoskeletal disorders such as knee osteoarthritis (OA) [1]. While much of the research in OA has focused on discrete outcomes (e.g., peak knee adduction moment [2–4]), the use of more data rich waveform-based methods may provide a better opportunity to assess the complexities of OA gait [5–7]. Moreover, univariate approaches fail to examine the important multidimensional interactions occurring at the knee joint (e.g., knee adduction and knee flexion moments [8,9]). Therefore, understanding the biomechanics of knee OA

gait is a complex, multivariate and multidimensional problem that can make the integration and interpretation of these data challenging, especially in a clinical setting.

The Gait Deviation Index (GDI) is a multivariate measure designed to address the issue of data complexity by providing a single, encompassing, value for one's deviation from a normative reference group. Schwartz and Rozumalski [10] initially developed the GDI to assess the overall gait pathology, or quality of gait, in children with cerebral palsy. The method utilizes a multivariate statistical approach to summarize multidimensional gait waveform data. In essence, the GDI allows for any individual's gait pattern to be compared to a reference group, in a manner similar to obtaining a multivariate z-score which

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describes the individual's overall deviation from the reference group. The deviation scored has been validated as a measure of gait quality, primarily in cerebral palsy [11–13], but can be easily applied to other clinical populations, including knee OA [14,15].

Naili et al. [14] compared the gait of individuals with severe knee OA awaiting a total knee arthroplasty to a group of healthy controls using the GDI. The authors found that individuals with knee OA not only demonstrated reduced GDIs compared to the healthy controls (i.e., lower quality gait), but that their GDIs were also related to functional and patient reported outcomes of activities of daily living, and quality of life. Therefore, the GDI may provide a unique opportunity to evaluate movement and loading patterns which can support decisions on OA treatment and risk of progression [14]. Nevertheless, while the work by Naili et al. [14] provides an interesting first take on the use of the GDI in knee OA, the current impact of these findings remains limited for several reasons. Most importantly, a limited sample of knee OA patients ($n = 40$), who walked significantly slower (1.1 m/s) than controls (1.3 m/s), was examined. To advance the clinical application of the GDI, there is a need to examine larger and more diverse knee OA samples in comparison to older and younger adults without knee OA, as these populations have been previously shown to have differences in gait patterns as compared to those with OA [16]. Further, it is important to examine the effect of gait speed on this relationship, as previous results were contradictory [15,17]. Finally, it is imperative to better understand the utility of the GDI by identifying meaningful differences (e.g., demographics and severity) between those with high and low GDIs.

Therefore, the purpose of this study was three-fold. The primary purpose was, i) to compare the GDIs, specific to sagittal and frontal plane knee angles and moments, across a large cohort of older individuals with knee OA (KOA), older adult controls without knee OA (CON), and young adults. Specifically, we hypothesized that a) CON would have lower GDIs (i.e., lower gait quality) than young adults and, b) KOA would have lower GDIs than both young adults and CON. The secondary purpose was ii) to examine the differences in GDIs across the three groups while addressing the potentially confounding effect of gait speed. We hypothesized that although the GDIs may be affected by gait speed, the between-group differences would remain significant after removing its confounding effect. Finally, unlike the abovementioned purposes which were hypothesis-driven, the final purpose was hypothesis generating, as we examined differences across KOA that displayed high and low GDIs. The third purpose was, iii) to examine how demographics, Kellgren and Lawrence (KL) grades, and gait waveforms compared across KOA with higher vs. lower GDIs.

2. Methods

2.1. Participants

All data were selected from a database constituted of study participants collected in our laboratory over the past 8 years. All participants were recruited from advertisements in print and social media, and using similar screening processes. No participants were recruited directly from the clinical setting. Young adults ($n = 52$) were included if they were between 18 and 40 years of age and free of pain, injury, or any musculoskeletal conditions that may affect their gait. Older adult controls without knee OA (CON; $n = 56$) were included if they: (1) were ≥ 40 years of age; (2) free of lower limb joint pain, injury, or any musculoskeletal conditions that may affect their gait; and (3) were free of radiographic knee OA (i.e., KL grade < 2).

Older individuals with knee OA (KOA; $n = 191$) were included if they: (1) were ≥ 40 years of age; (2) had definitive medial tibiofemoral osteophytes on X-ray; (3) joint space narrowing greater in the medial tibiofemoral compartment compared to the lateral compartment; (4) history of knee pain longer than 6 months; and (5) average knee pain of at least 3 out of 10 over the last month. Individuals were excluded if

they had: (1) knee surgery or intra-articular injections within 6 months; (2) oral corticosteroid use within 6 months; (3) history of knee joint replacement or tibial osteotomy; or (4) any other condition affecting lower limb function.

2.2. Data collection and analysis

Gait trials were collected as barefoot, over ground walking at the participant's self-selected speed, with a standardized 22-marker Helen Hayes markerset [18] and optoelectronic motion capture cameras (Motion Analysis Corp, Santa Rosa, CA, USA) collecting at 120 Hz. Kinematic data were synchronized with two force platforms (OR6-6, Advanced Mechanical Technologies Inc.) mounted in the floor of a 10 m walkway and sampling at 1200 Hz. Knee joint kinematics and kinetics were calculated using the joint coordinate system [19] with commercially available software (Orthotrak, Motion Analysis Corp., Santa Rosa) and ensemble average waveforms were generated from 5 time-normalized stance phases for each individual.

The GDI was calculated using ensemble average frontal and sagittal plane knee joint angles and moments. These four ensemble average curves were concatenated into a 404-point data vector (i.e., 101 per waveform) for each participant. Using the method described by Schwartz and Rozumalsk [10], data from the healthy reference group (i.e., young adults) were reduced to a set of principal components (PCs) which explained 98% of the variance in the original data. The GDI calculation is presented in a Supplementary MATLAB (The MathWorks, Natick, MA, USA) function which can be used to compute GDIs in comparison to a reference dataset. Briefly, given the use of kinematics and kinetics, all input data was scaled to a mean of 0 and a standard deviation of 1 prior to data reduction [10]. The loading coefficients for each PC were then used to project the new, scaled data vectors of KOA and CON into the young adult-defined subspace. Each GDI was then calculated as the composite and scaled difference between an individual's gait features (i.e., PCs) and the average gait features of young adults. Therefore, this metric relates to the Euclidean distance between an individual's gait data (i.e., ensemble average frontal and sagittal plane knee joint angles and moments) and the gait data of the young adult cohort. In the current application, a score of ≥ 100 represents a typical pattern at the knee, similar to the young adult group, with each 10-point decrease representing one standard deviation from typical. To further compare the GDIs of KOA and CON to healthy young adults, a leave-one-out approach (i.e., model derived on $n-1$ young adults and GDI computed for the left-out participant) was used to derive individual GDIs for each young adult.

2.3. Statistical analysis

2.3.1. Primary purpose

Group differences in GDIs were assessed using a one-way analysis of variance ($\alpha = 0.05$), with post-hoc LSD tests to measure pairwise differences between groups. Uncorrected post-hoc tests were used as there were a limited number of comparisons and those comparisons were directional hypotheses [20]. Assumptions of normality and equality of variances were examined with Kolmogorov-Smirnov and Levene's tests, respectively. All statistical analyses were performed using IBM SPSS Statistics 24.0 (SPSS Inc., Armonk, NY).

2.3.2. Secondary purpose

To address the potential confounding effect of gait speed, two independent methods were used. First, a conventional statistical approach was used involving an analysis of covariance ($\alpha = 0.05$), with gait speed as the covariate. However, given the potential limitations of this method (e.g., altering means and limiting interpretation [21]), an alternative and novel approach was used which randomly resampled groups based on the gait speed distributions (i.e., probability density function) of the young adult group. This allowed for the random

generation of a subset of 52 KOA and 52 CON which displayed gait speeds similar to the 52 young adults. Group differences in the GDIs of these speed-resampled subsets were then examined using a one-way analysis of variance ($\alpha = 0.05$) and post-hoc LSD tests as above.

2.3.3. Tertiary purpose

KOA subgroups were further examined based on higher vs. lower GDIs. Specifically, the mean GDI obtained from CON was a priori defined as the cut-off value for these groups. Student's t-tests ($\alpha = 0.05$) and effect sizes (Cohen's *d*) were used to compare demographics such as: age, body mass index, and gait speed between subgroups. Chi-square tests ($\alpha = 0.05$) and effect sizes (Cramer's *V*) were used to compare the sex and KL grade distribution between OA subgroups. Lastly, PC scores, used to calculate GDIs, were compared across knee OA subgroups using an analysis of variance ($\alpha = 0.05$).

3. Results

3.1. Sample and model

KOA were significantly older ($p = 0.002$), had a greater body mass index ($p < 0.001$), and walked slower ($p < 0.001$) than CON (Table 1). However, these differences were negated in the speed-resampled subsets, with body mass index being the only variable that remained significantly different between KOA and CON ($p = 0.014$). The most common KL grade for KOA was grade 2 (49%), followed by grade 3 (39%), and grade 4 (12%). All CON had KL grades of either grade 0 (57%) or grade 1 (43%). The GDI model was based on 14 PCs which described 98.03% of the variance in the young adult knee kinematic and kinetic gait data. However, the majority of variance (85%) was explained in the first 5 PCs.

3.2. Primary purpose – between groups

CON displayed significantly lower GDIs (94.3 (11.0)) compared to young adults (99.6 (10.6); $p = 0.014$). KOA also displayed significantly lower GDIs (87.2 (11.1)) compared to young adults ($p < 0.001$) and CON ($p < 0.001$; Table 1, Fig. 1, and Supplementary Table 1). Frontal and sagittal plane joint kinematic and kinetic ensemble average waveforms for all groups are presented in Fig. 2.

3.3. Secondary purpose – gait speed

While KOA displayed significantly reduced gait speeds compared to both young adults (1.19 (0.17) m/s vs. 1.34 (0.13) m/s, $p < 0.001$) and CON (1.19 (0.17) m/s vs. 1.31 (0.17) m/s, $p < 0.001$), correcting for this difference did not change the results. Specifically, including gait speed as a covariate had little impact on the GDI results above. The GDIs of CON remained significantly lower than young adults ($p = 0.019$) and the GDIs of KOA remained significantly lower than

both young adults ($p < 0.001$) and CON ($p < 0.001$). Similarly, the random resampling technique created subsets of the original groups with the same sample sizes ($n = 52$) and similar gait speeds ($p = 0.168$). However, this also did not change the results; the GDIs of CON remained significantly lower than young adults ($p = 0.025$) and the GDIs of KOA remained significantly lower than both young adults ($p < 0.001$) and CON ($p = 0.002$; Table 1, Fig. 1, and Supplementary Table 1).

3.4. Tertiary purpose – within OA

KOA were subgrouped based on whether they displayed a GDI above or below the mean value from the CON (GDI = 94.3). A total of 56 KOA (29%) had a GDI above this cut-off, while 135 KOA (71%) had a GDI that was below this cut-off. Overall, there were no differences in these subgroups across demographics, KL grade, or self-selected walking speed (Table 2).

Given that the KOA subgroups were specifically created based on high and low GDIs, the significant differences observed in the GDI score itself ($p < 0.001$), as well as half of the PC scores ($p < 0.05$), were not surprising. Nevertheless, the Levene's test for equality of variances failed in this KOA subgroup comparison for the GDI ($p < 0.001$), as well as nearly half of the PCs scores ($p < 0.05$; Supplementary Table 2). This inequality of variance between KOA subgroups can also be visualized in Fig. 3, as individuals with lower GDIs appeared to demonstrate greater variability in gait patterns.

4. Discussion

The primary purpose of the study was to compare knee-specific GDIs across a large cohort of KOA, CON, and young adults. As hypothesized, we observed significant differences in the GDI across all groups, with KOA displayed the lowest GDIs (i.e., lowest quality gait). Moreover, while CON remained within one standard deviation (i.e., $GDI \geq 90$ [10]) of the reference young adult gait pattern, KOA did not. Second, as hypothesized, we found that these relationships remained consistent even after controlling for differences in gait speed. While these findings suggest the knee-specific GDI is a viable multivariate statistical tool for assessing holistic gait pattern deviations between groups, the clinical utility of an individual GDI score requires further examination.

KOA demonstrated significantly greater overall knee kinematic and kinetic pattern deviations than CON. This finding supports previous research using the GDI in knee OA [14] and hip OA [15] populations awaiting total joint arthroplasty. The current findings also extend these results to a larger, more heterogeneous cohort of individuals with moderate to severe knee OA (i.e., KL grade 2–4). Although the methodological approach varies from previous knee OA classification studies (e.g., unsupervised vs. supervised learning [5,6,22]), these results further support the utility of multivariate, waveform-based gait pattern assessments for separating healthy and knee OA gait patterns [5–7].

Table 1

Demographics and Gait Deviation Index (GDI) results for the young adults, older adult controls without knee OA (CON), and older individuals with knee OA (KOA), as well as the speed-resampled subsets.

Sample (n)	Young Adults	CON		KOA	
	Full Sample (52)	Full Sample (56)	Speed-resampled (52)	Full Sample (191)	Speed-resampled (52)
Age (yrs)	26.1 (4.4)	60.5 (9.5)*	60.4 (9.8)*	64.8 (9.4)* †	61.5 (8.4)*
Sex (F - M)	25 F - 26M	22 F - 34M	20 F - 32M	64 F - 127M	26 F - 26M
BMI (kg/m ²)	22.6 (2.7)	24.4 (3.6)	24.4 (3.5)*	27.2 (4.3)* †	26.8 (4.3)* †
KL Grade (% 0-4)	N/A	57-43-0-0-0	62-38-0-0-0	0-0-49-39-12	0-0-60-36-4
Gait Speed (m/s)	1.34 (0.13)	1.31 (0.17)	1.34 (0.12)	1.19 (0.17)* †	1.30 (0.10)
GDI (unitless)	99.6 (10.6) [#]	94.3 (11.0)*	94.9 (10.9)*	87.2 (11.1)* †	88.5 (9.9)* †
GDI 95% CI	96.6 - 102.5	91.4 - 97.3	91.9 - 98.0	85.3 - 88.8	85.7 - 91.3

*Significant difference from young adults; †Significant difference from CON; #Calculated using leave-one-out validation method.

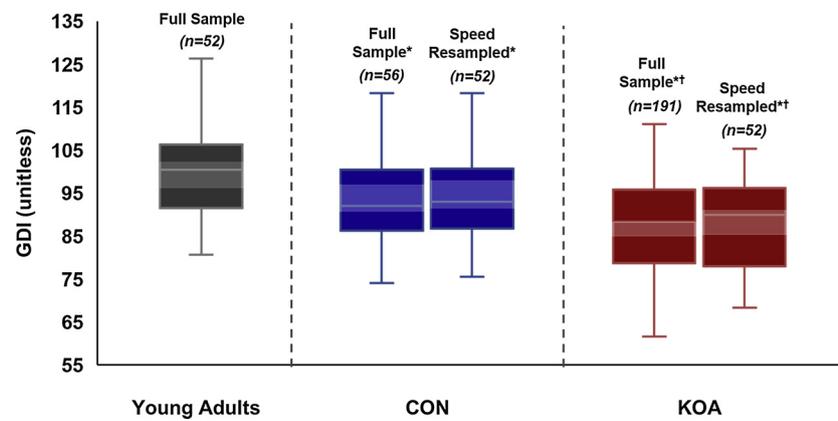


Fig. 1. Box and whisker plots of Gait Deviation Indices (GDIs) across young adults (grey), older adult controls without knee OA (CON; blue), and older individuals with knee OA (KOA; red), with 95% confidence intervals highlighted in white. *Significantly different from young adults. †Significantly different from CON.

Given the potential effect of gait speed on joint kinematics and kinetics [21,23] and the GDI itself [17], the secondary purpose of the study was to further examine differences in GDIs between groups, while controlling for walking speed. It is well known that people with knee OA, especially those with severe disease, exhibit slower preferred gait speeds compared to healthy controls [24]. However, as hypothesized, the differences initially observed in the GDIs between groups remained significant, even after controlling for gait speed with two separate methods. This finding is similar to Rosenlund et al. [15] who found that gait speed had a limited impact on the GDIs association with muscle strength and patient reported outcomes. On the other hand, while previous research has demonstrated that gait speed can impact the GDI, this was primarily found at slow walking speeds (e.g., > 20% reduction in gait speed) [17]. Therefore, the differences in gait speed of 10–15% between groups in the current data and Rosenlund et al. [15] are likely not large enough to cause a significant deviation in gait patterns. In other words, given that the GDI is measuring a deviation of an overall gait pattern, it is likely that it is largely unaffected by reasonable changes (i.e. < 20%) in gait speed. However, this limited sensitivity may hinder its clinical utility on an individual basis in a knee OA

Table 2

Demographics and Gait Deviation Index (GDI) results for subgroups of older individuals with knee OA, as defined by the GDI = 94.3 cut-off from older adult controls without knee OA. All outcomes were examined using either a Student’s t-tests or chi-square test (p-value), with Cohen’s d or Cramer’s V effect sizes (ES), respectively.

	High GDIs	Low GDIs	p-value	ES
N	56	135	–	–
Age (yrs)	63.2 (9.0)	65.4 (9.5)	0.129	0.24
Sex (F - M)	38 F - 18M	89 F - 46M	0.797 ^a	0.02
BMI (kg/m ²)	26.5 (3.9)	27.5 (4.5)	0.157	0.24
KL Grade (% 1-4)	0-0-50-41-9	0-0-49-38-13	0.758 ^a	0.06
Gait Speed (m/s)	1.21 (0.15)	1.18 (0.18)	0.160	0.18
GDI (unitless)	99.8 (4.3) [*]	82.0 (8.6) [*]	< 0.001	2.62
GDI 95% CI	98.7 - 101.0	80.6 - 83.5	–	–

* Significant difference between groups.

^a Chi-Square test for significance.

population.

The final purpose was to examine differences across KOA who

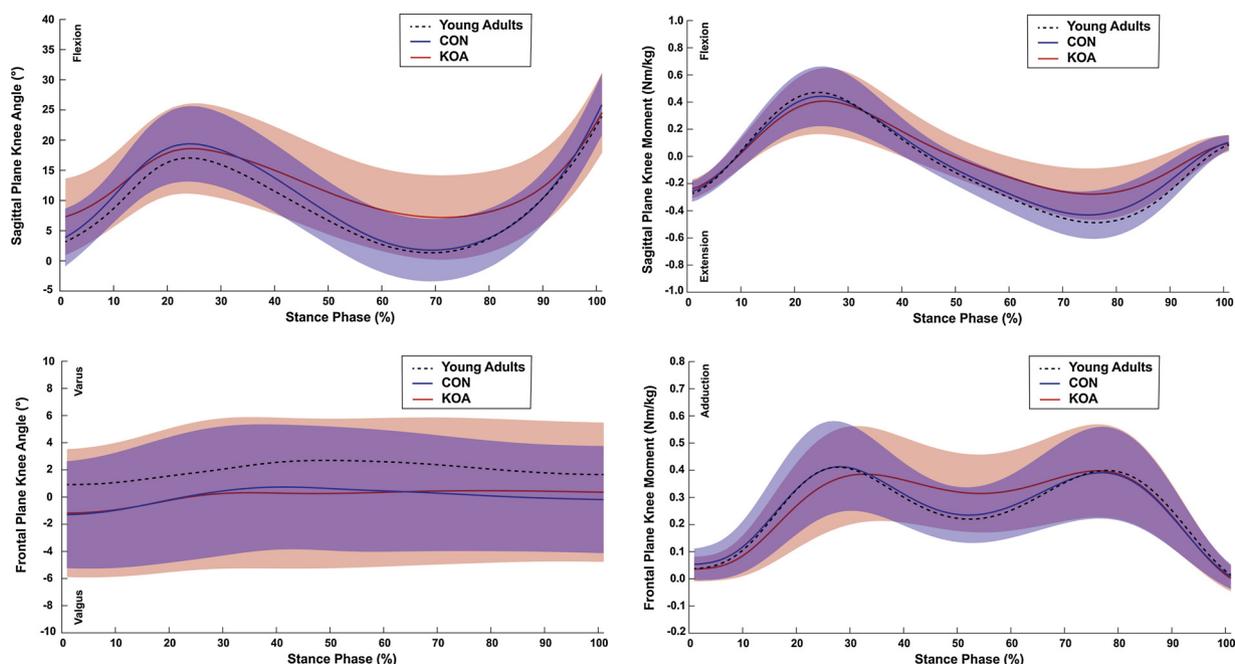


Fig. 2. Knee joint kinematics and kinetics presented for young adults (black dashed), older adult controls without knee OA (CON; blue), and older individuals with knee OA (KOA; red). The shaded areas around the ensemble average curve represent one standard deviation.

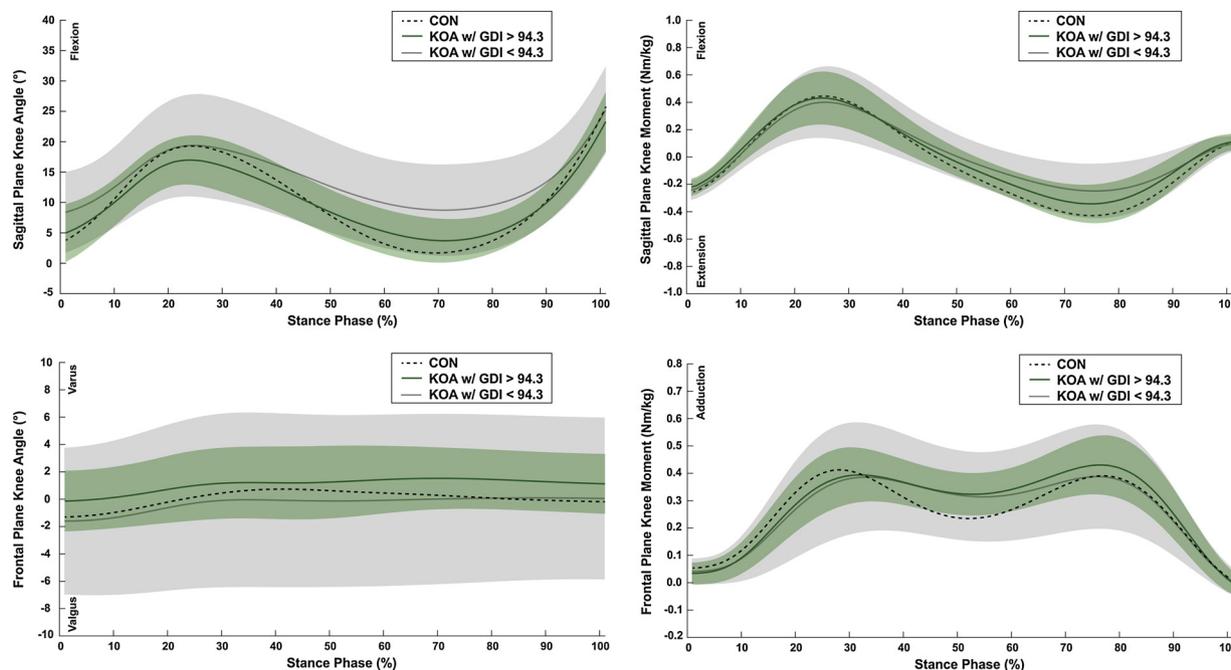


Fig. 3. Knee joint kinematics and kinetics presented for older individuals with knee OA (KOA) above (green) or below (grey) a Gait Deviation Index (GDI) of 94.3, as well as older adult controls without knee OA (CON; black dashed). The shaded areas around the ensemble average curve represent one standard deviation.

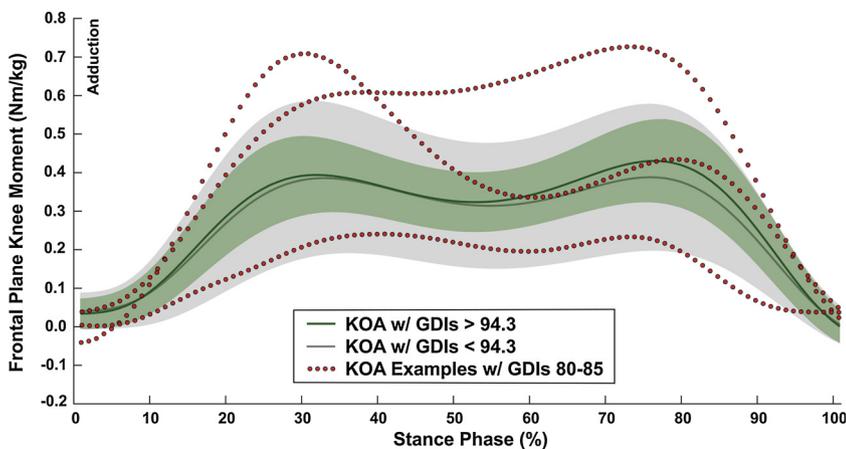


Fig. 4. Knee adduction moment in older individuals with knee OA (KOA) above (green) or below (grey) a Gait Deviation Index (GDI) of 94.3. Three representative individual waveforms (red circles) are presented to illustrate the variance in individual gait patterns present in the low GDI subgroup. The shaded areas around the ensemble average curve represent one standard deviation.

displayed high vs low GDIs, in the hope of shedding light on the potential clinical utility of the GDI. Unfortunately, no systematic differences were present in any demographic or radiographic data between subgroups (Table 2). While these null findings may appear to limit the clinical utility of a GDI for subgrouping OA patients, it is important to understand the underlying purpose of this measure. The GDI is designed to measure the overall magnitude of multidimensional deviations from a typical gait [10], not to identify similar patterns or subgroups. In other words, individuals with low GDIs are only similar in that they have a similar overall magnitude of deviation, but the deviation itself may occur in a variety of ways. This was observed statistically (i.e., failed Levene’s tests) and more directly in the knee adduction moment waveforms shown in Fig. 4. Here, it is evident that although the mean waveforms may look similar between low and high GDIs, lower scoring individuals display highly variable and deviant patterns that are poorly represented by the misleading subgroup ensemble average waveform. This concept of increased variability and deviation occurring in the gait patterns of knee OA populations directly supports previous multivariate analyses [22,25,26]. While this finding limits the clinical utility of a single GDI value, it further supports the need for better subgroup or individual-specific analyses, in contrast to presenting a conventional

group ensemble average waveform or making comparisons across such heterogeneous cohorts.

Finally, while the GDI may lack the ability to define specific differences in gait patterns, and needs to be interpreted with caution on an individual basis, it may still provide a useful “red-flag” metric or longitudinal tracking metric. For example, the GDI can effectively assess whether an individual’s overall gait pattern fits within that of a given population. Therefore, the GDI may provide utility as an automated check of an individual’s data before undergoing further analysis. For example, this data analysis approach could be useful in curating clinical and/or normative gait biomechanical databases. In other words, incoming data could be screened using the GDI to flag individuals with gait patterns that deviate from the majority and may introduce unwarranted variability into the dataset. Lastly, the GDI may present utility in tracking longitudinal gait pattern changes in comparison to a reference group [14]. While a similar unsupervised, but within-subjects model has been shown to be highly sensitive to individual changes following an intervention [27], the GDI may provide the advantage of longitudinal tracking in reference to a group of interest. Nevertheless, given the GDIs limited sensitivity to covariates such as gait speed, it is unclear how sensitive it may be to detecting gait

pattern changes over time.

There are limitations that should be discussed in the current study. First, our GDI is specific to knee biomechanics. While this is unique from other GDI research in OA [14,15], we felt that focusing on a knee-specific score may provide the most relevance for the population. Further, the initial GDI research [10] suggested the potential utility of a joint specific GDI. Second, this method requires the use of a conventional motion capture system, making the access to such a measure limited, especially in a clinical setting. Alternatively, accessible wearable sensor biomechanical data [28–31] could be used to compute a wearable sensor specific GDI that would allow for accessible gait pattern comparisons and longitudinal tracking. Nevertheless, there is a need to further validate the use of such devices with a GDI.

5. Conclusion

A knee-specific GDI found increased gait pattern deviations in KOA, as compared to both CON and young adults. Further, controlling for gait speed using two separate methods did not significantly alter the between-group differences. The GDI appears to be effective in identifying overall effects of gait pattern deviation and may provide some utility as a biomechanical “red-flag” metric. Nevertheless, an individual GDI score alone is unlikely to provide clinically actionable information for individuals with OA.

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Conflict of interest statement

The authors confirm that they have no conflicts of interest to declare regarding this work.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.gaitpost.2019.05.020>.

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