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Lower limb gait joint coordination variability in people with diabetes-related foot ulcers

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ABSTRACT

Background: Diabetes-related foot ulcers pose substantial health risks globally, yet the biomechanical intricacies underlying their development remain incompletely understood. This study aimed to evaluate lower limb gait joint coordination variability in individuals with diabetes-related foot ulcers compared to those with diabetes (without diabetes-related foot ulcers) and healthy controls.
Methods: A total of 99 participants (diabetes-related foot ulcers cases – 16, Diabetes controls – 50, Health controls – 33) compared three self-paced walking trials. Vector coding, a technique quantifying movement coordination, was employed, analysing hip-knee, knee-ankle, and hip-angle joint couplings in the sagittal plane.
Findings: No significant differences in coordination variability were found among the groups. However, distinct coupling pattern frequencies emerged, with diabetes-related foot ulcers cases exhibiting unique anti-phase hip and ankle coupling frequency counts compared to healthy controls.
Interpretation: These findings challenge conventional understandings of diabetes-related foot ulcers biomechanics and underscore the complexity of gait in this population.

1. Introduction

Diabetes-related foot ulcers (DFUs) are a leading cause of hospitalisation, amputation and disease burdens, globally (Armstrong et al., 2017; Lazzarini et al., 2023a; Lazzarini et al., 2024b; Zhang et al., 2020). People with DFU have significantly poorer health-related quality of life than those with other diabetes-related complications and many other well-known diseases (Byrnes et al., 2024; Wukich and Raspovic, 2018).

Major contributing factors to DFU include diabetes-related peripheral neuropathy (DPN) and peripheral artery disease (PAD)(Armstrong et al., 2017; Lazzarini et al., 2023b; Schaper et al., 2024). DPN has sensory, motor and autonomic components (Pop-Busui et al., 2017). Sensory DPN has received the most extensive investigation with the loss of protective sensation being the predominant component implicated in DFU formation (Armstrong et al., 2017; Lazzarini et al., 2023b; Schaper et al., 2024). Motor DPN, on the other hand, has received less attention even though it also has significant implications for the development of DFUs via altered lower limb biomechanics and in turn high plantar pressures (Mueller et al., 1994; Veves et al., 1992).

Altered biomechanical characteristics include joint angular kinematic changes (such as increased hip flexion and knee extension), kinetic (ground reaction force) changes (such as reduced braking and propelling force) and temporospatial parameters (TSPs) changes (such as a longer stance time) (Fernando et al., 2013). These biomechanical changes are the outcomes of restricted lower limb joint range of motion (RoM) and subsequent foot-joint deformities which contribute to elevated plantar pressure (Barn et al., 2015; Chuter et al., 2012; Lazzarini et al., 2019). Elevated plantar pressure during gait in the presence

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Table 1
Descriptive characteristics of participants with diabetes related foot ulcers (DFU cases), diabetes controls and healthy controls.

	DFU cases ($n = 16$)	Diabetes controls ($n = 50$)	Healthy controls ($n = 33$)
Gender (M/F)	M = 13 F = 3	M = 31 F = 19	M = 20 F = 13
Age (yrs)	62.6 ± 10.3	61.4 ± 10.2	60.8 ± 10.6
Height (m)	1.75 ± 8.5	1.70 ± 9.5	1.70 ± 10.7
Body mass (kg)	103.7 ± 22.4	88.8 ± 16.3*	80.3 ± 16.1*†
BMI (kg/m^2)	34.1 ± 8.0	30.8 ± 5.0*	27.6 ± 4.9*†
Body fat (%)	27.8 ± 15.3	27.7 ± 11.9	24.9 ± 11.5
Waist circumference (cm)	114.5 ± 17.1	103.4 ± 14.4*	93.4 ± 14.3*†
Hip circumference (cm)	112.5 ± 20.1	102.9 ± 14.4	103.0 ± 56.0
W:H ratio	1.02 ± 0.07	1.01 ± 0.08	0.98 ± 0.15
Cadence (steps/min)	106 ± 8	108 ± 10	113 ± 8*†
Gait speed (m/s)	0.94 ± 0.22	1.05 ± 0.18	1.17 ± 0.14*†

* $P < 0.05$ vs. DFU cases; † $P < 0.05$ vs. Diabetes controls; DFU – diabetes related foot ulcer; BMI – body mass index; W:H – waist to hip ratio.

of sensory DPN increases plantar tissue trauma and predisposes people to DFUs (Armstrong et al., 2017; Lazzarini et al., 2023b; Schaper et al., 2024) and if not addressed to DFU recurrence (Aan de Stegge et al., 2020; Armstrong et al., 2017).

The majority of research investigating biomechanical characteristics in those with DPN has focused on assessing plantar pressures before the development, or after the healing, of DFUs (Lazzarini et al., 2024a; van Netten et al., 2024). Previous research has suggested that reducing elevated plantar pressures on the foot prevents DFUs from occurring and allows optimal healing of plantar DFUs (Fernando et al., 2014; Lazzarini et al., 2024a; van Netten et al., 2024). Hence current international guidelines recommend achieving at least a 30 % reduction in maximum plantar pressure to prevent and heal foot ulcers (Bus et al., 2024a; Bus et al., 2024b; Fernando et al., 2022). Offloading interventions, such as total contact casts, removable cast walkers, footwear and surgery have been effective in lowering plantar pressure while DFUs are healing (Lazzarini et al., 2024a). More detailed biomechanical characteristics (TSPs, kinematics and kinetics) potentially contributing to these elevated plantar pressures though remain poorly understood (Fernando et al., 2013). Research has demonstrated that although restricted RoM in the lower limbs during walking in people with DPN has been associated with elevated plantar pressure (Barn et al., 2015; Fernando et al., 1991; Fernando et al., 2016c; Fernando et al., 2017), any association between gait kinematics and elevated plantar pressure in people with DFUs remain unknown. A previous case-control study demonstrated that individuals with foot ulcers had reduced plantarflexion, knee flexion and pelvic obliquity compared to controls with and without diabetes (Fernando et al., 2016b; Fernando et al., 2019). Additionally, individuals with DFU had greater range force in the anterior-posterior vector and total vertical ground reaction force, and slower walking speed with smaller step length compared to controls (Fernando et al., 2016b; Fernando et al., 2019). Although this research has indicated the potential impact of DFU on gait kinematics and kinetics, the variables reported are single linear measures and did not assess the complexity of gait mechanics from a coordination relationship i.e. intra-joint coordination variability across the entire stride.

To measure intra-joint coordination variability the modified vector coding technique can be used to quantify movement coordination between two joints/segments over time, often applied to angle-angle diagrams (Chang et al., 2008; Hamill et al., 2000; Needham et al., 2015; Sparrow et al., 1987). The technique introduces the concept of a coupling angle, indicating the vector orientation between adjacent time points on such diagrams, relative to the right horizontal axis, additionally the angle can be placed into 45-degree bins, allowing for classification of coordination patterns, offering insights into functional movements like gait. Researchers have used this technique to demonstrate that there are coordination variability differences between flatfoot and neutral foot runners, which may explain why flatfoot runners experience running injuries (Takabayashi et al., 2023). Other research has demonstrated that the hip-knee joint coupling angle during mid-stance was associated with knee injury and osteoarthritis outcomes score (KOOS) pain (Huang et al., 2023).

To our knowledge there has only been one study that has examined variability in neuropathic patients (Dingwell et al., 1999b). This research did find trends towards increased variability in gait among diabetic neuropathic and diabetic non-neuropathic vs. controls during controlled treadmill walking. However, the study only used stride-to-stride standard deviation and coefficients of variation to explore variability. Utilisation of the modified vector coding technique may provide a comprehensive biomechanical investigation of participants with DFU and may identify abnormal gait characteristics throughout the entire gait cycle instead of discrete time points (Bus et al., 2024a; Bus et al., 2024b; Formosa et al., 2013). This knowledge may allow for a more precise formulation of tailored treatments that include existing off-loading options and potential future biomechanical interventions (Bus et al., 2024a; Bus et al., 2024b).

Therefore, the aim of this study was to comprehensively assess lower limb gait joint coordination variability in individuals with DFUs (DFU cases) compared to individuals with type 2 diabetes without a history of DFUs (diabetes controls) and individuals without type 2 diabetes or a foot ulcer (healthy controls). It was hypothesised that compared to controls, cases with DFUs would display reduced coordination variability measures during self-paced barefoot gait.

2. Methods

2.1. Study design and setting

This was a case-control study nested in a six-month longitudinal research project, conducted in a single regional Australian site (Townsville, Australia). A full study protocol has been previously published (Fernando et al., 2015). In brief, there were three groups of eligible participants: individuals with type 2 diabetes with an active plantar neuropathic ulcer (DFU cases); individuals with type 2 diabetes without a history of foot ulceration (diabetes controls); and individuals without a history of type 2 diabetes or a foot ulcer (healthy controls). The control groups were matched, based on sex and age range of plus or minus five years, to the cases. The study was approved by two local human research ethics committees, and the approval numbers were HREC/12/QTHS/77 and H4693. Written informed consent was obtained from all participants involved in this study prior to initial assessment.

2.2. Participants

All participants were recruited from the Townville hospital and health services region (Queensland, Australia) over a two-year period. Participants with type 2 diabetes were recruited from outpatients and inpatients attending the Townsville Hospital and Health Services facilities and via referral from local health practitioners. Healthy controls were recruited via community advertising and among university staff where the study took place. Since this was a secondary analysis of our research (Fernando et al., 2016b), a power analysis was not pre-planned.

Inclusion criteria for cases included adults (18 years or older) with a confirmed diagnosis of type 2 diabetes and a single active unilateral plantar DFU of longer than 3 months duration. The diabetes controls comprised of adults with a confirmed diagnosis of type 2 diabetes without a history of DFUs. The healthy controls comprised of adults without a history of diabetes or DFUs. The exclusion criteria were designed to avoid inclusion of patients with problems impacting on mobility that would likely mask the impact of a plantar foot ulcer on gait. Exclusion criteria for all participants included: (1) orthopaedic, musculoskeletal, vestibular, visual or neurological problems affecting mobility (other than DPN); (2) previous orthopaedic surgical

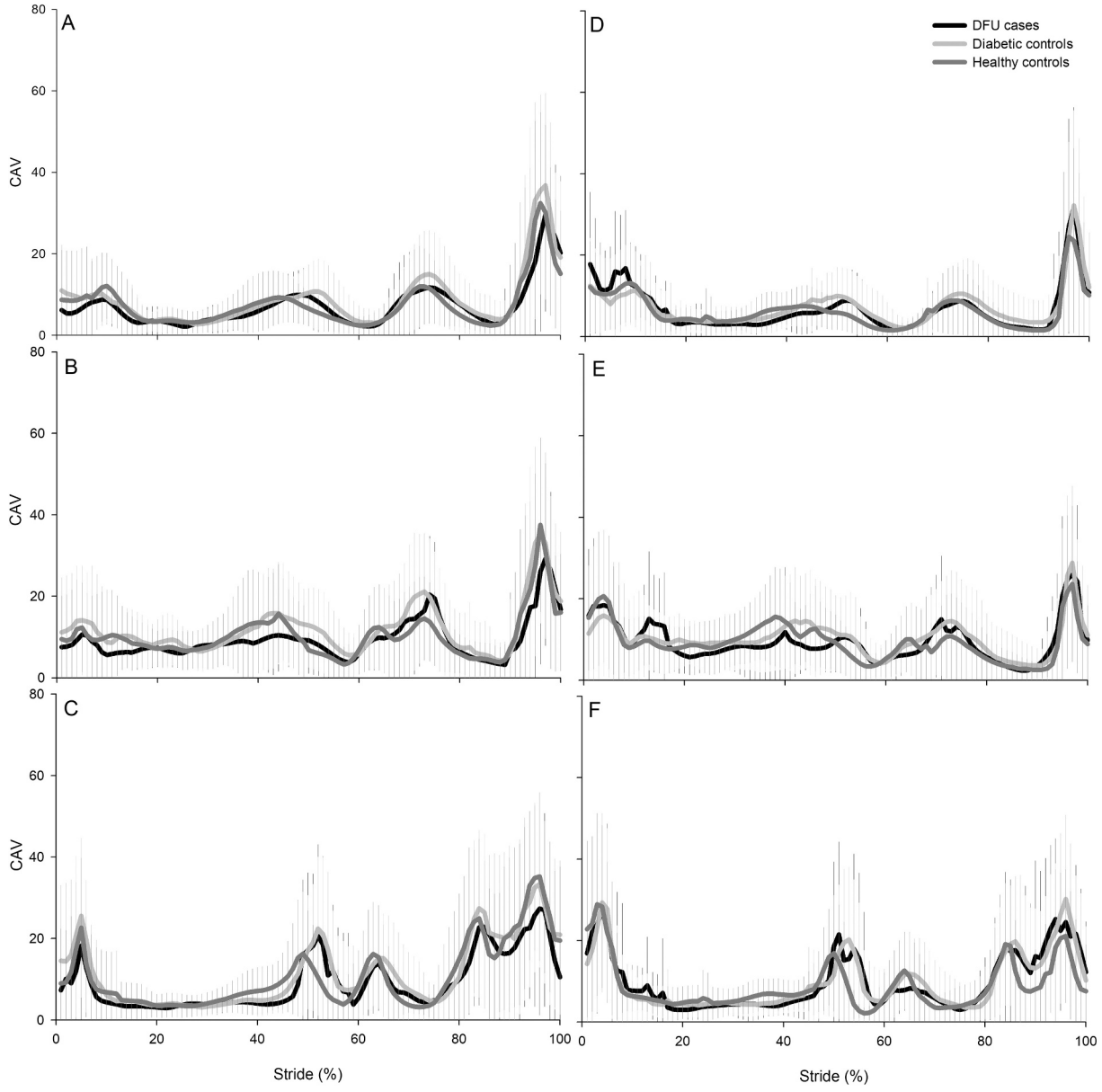

Fig. 1. (A) Left Hip-Knee joint coordination angle variability; (B) Left Knee-Ankle joint coordination angle variability; (C) Left Hip-Ankle joint coordination angle variability; (D) Right Hip-Knee joint coordination angle variability; (E) Right Knee-Ankle joint coordination angle variability; (F) Right Hip-Angle joint coordination variability. DFU - DFU cases – Black line; DMC - diabetes controls - Grey line; HC - healthy controls - Dark grey line; Vertical lines indicated +/− standard deviation; CAV – coupling angle variability.

intervention of the lower limb that potentially altered the participant's original gait; (3) diabetes types other than type 2 diabetes; (4) peripheral arterial disease defined as an ankle-brachial pressure index (ABPI) of <0.8 in either limb; (5) planned vascular reconstructions in the subsequent 12 months; and (6) pregnancy (Fernando et al., 2015).

2.3. Variables collected

A pre-defined and detailed case report form was used for collecting demographic, co-morbidity, anthropometric and clinical domains of explanatory variables using pre-established methods, as previously described (Fernando et al., 2015). Demographic variables reported in this study included: age and sex. Anthropometric variables included height, body mass, body mass index (BMI), body fat percentage, waist and hip circumferences.

2.4. Procedures for three-dimensional movement analysis

Each participant performed three self-paced gait assessments at a natural pace of walking without enforced conditions (Kanade et al., 2006; Raspovic, 2013). One trained investigator (MEF) conducted all assessments based on standard protocols. The procedures used for the collection of the outcome variables have been described in detail previously (Fernando et al., 2015). In brief, the VICON gait analysis system (VICON, Oxford, United Kingdom) consisting of ten T-40 series infrared cameras were positioned around a gait environment capturing at 100 Hz. VICON Nexus movement analysis software was used for three-dimensional movement analysis (version 1.9.1, VICON, Oxford, United Kingdom). The force plates in the laboratory comprised two 400 × 600 mm OR-6 AMTI force plates and two 900 × 900 mm OR-6 AMTI force plates (AMTI, Watertown, Massachusetts, USA) which were embedded on a 10 m long gait surface covered by concrete overlay. A standard VICON Nexus procedure (Plug-in Gait model) was used during motion

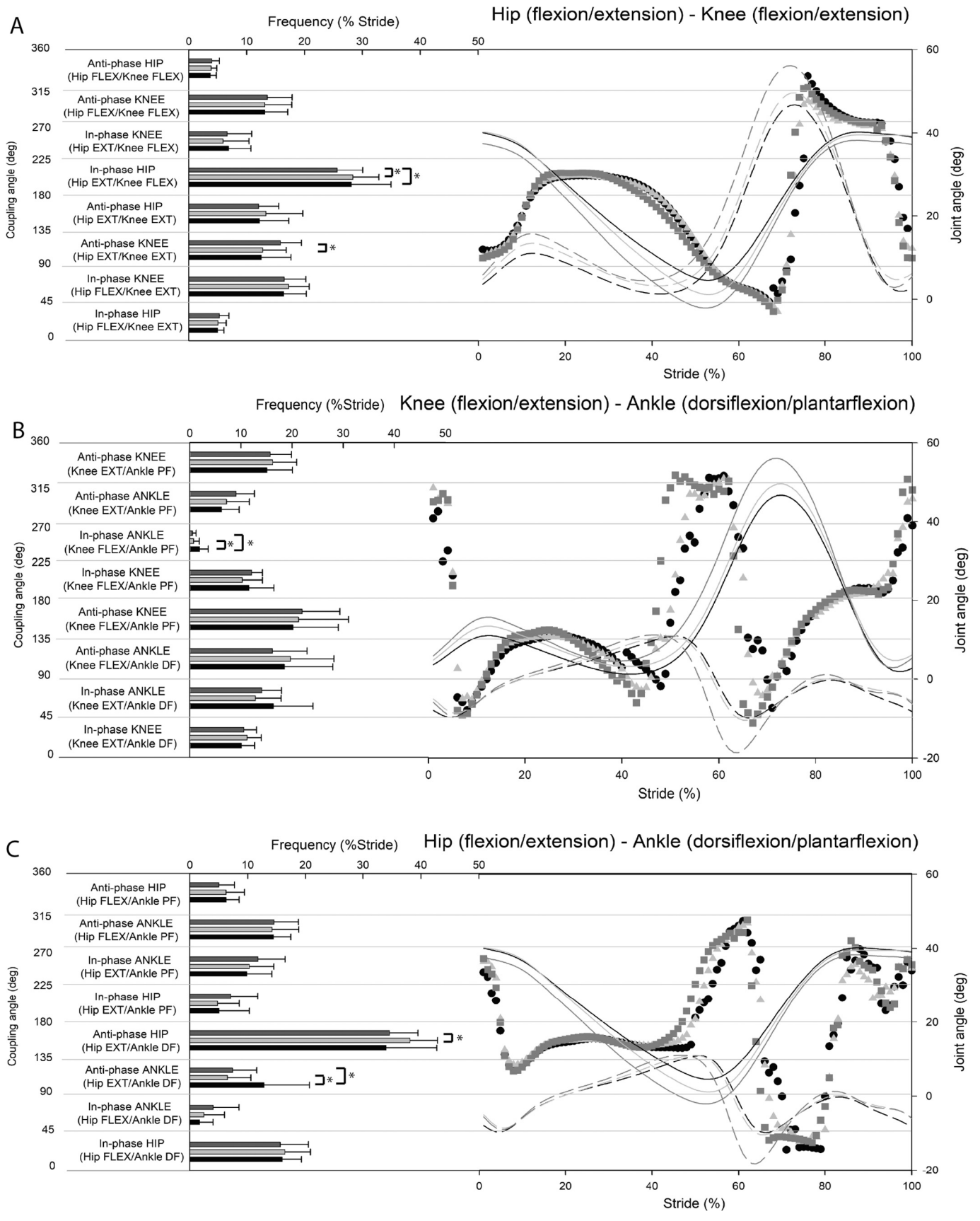

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Fig. 2. (A) Mean coupling angle for hip-knee coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – hip angle solid line; knee angle medium dash line), and pattern frequency (Y1 - bars) for the left stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. (B) Mean coupling angle for knee-ankle coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – knee angle solid line; ankle angle medium dash line), and pattern frequency (Y1 - bars) for the left stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. (C) Mean coupling angle for hip-ankle coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – hip angle solid line; ankle angle medium dash line), and pattern frequency (Y1 - bars) for the left stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. FLEX – Flexion; EXT – Extension; DF – Dorsiflexion; PF – Plantarflexion.

capture (Vicon Motion Systems, Oxford, England). The coefficient of variation for the assessment of gait data were all within the pre-established acceptable level of less than 10 % and the ability of the operator to identify anatomical landmarks had concordance correlation coefficients of above 0.90 suggesting good to excellent reproducibility as previously reported (Fernando et al., 2016a).

All gait assessments were reconstructed and labelled, and gaps filled in VICON Nexus (v2.10, VICON, Oxford, UK). A fourth order zero-lag low-pass Butterworth filter with 6 Hz cut-off frequency was used to smooth marker trajectory. Joint angular kinematics for the hip, knee and ankle for the sagittal plane only (medial-lateral axis) were calculated in VICON Nexus and exported as CSV files. A custom written code in MATLAB (Matlab R2018a, MathsWorks, Natick, MA) was used to normalise the gait cycle to 101 data points. Coordination variability was calculated using a modified vector coding technique (Chang et al., 2008) for each participant across the gait cycle for left and right limbs. The primary outcome (coupling angle variability) was calculated as the standard deviation of the vector connection corresponding consecutive time point of the joint-joint coordination plots across all trials using circular statistics (Chang et al., 2008). The following joint-joint couplings were examined: hip (flexion/extension) – knee (flexion/extension), knee (flexion/extension) – ankle (dorsiflexion/plantarflexion) and hip (flexion/extension) – ankle (dorsiflexion/plantarflexion). Additionally, the secondary outcome (coupling pattern frequency) were classified into in-phase with proximal dominancy, in-phase with distal dominancy, anti-phase with proximal dominancy and anti-phase with distance dominancy (Needham et al., 2015).

2.5. Statistical analysis

Mean and standard deviations (SD) were calculated for all variables for each group. Participant characteristics and coupling pattern frequency statistical analyses were conducted using SPSS statistical software (v28, IBM Cop., Armonk, USA). Boxplots were used to identify outliers (identified as being below the lower bound or above the upper bound - no data was removed) and Shapiro-Wilk test was used to check for data normality (data was not normally disturbed for coupling pattern frequency). Participant characteristics were assessed using one-way ANOVA. Differences between groups (DFU cases vs. diabetes controls vs. healthy controls) for coupling pattern frequency were assessed using Kruskal-Wallis with a post hoc Bonferroni correction factor. Quantile regression was used to examine how body mass and gait speed influenced coupling pattern frequency across different points in its distribution, allowing for the detection of potential differential effects not observable through mean-based analyses. Analyses were conducted at the 25th, 50th, and 75th quantiles to assess these covariates' impacts across the range of coupling frequencies, with robust standard errors applied to account for any data variability. One-dimensional statistical parametric mapping (SPM1D) one-way ANOVA was used to compare coupling angle variability waveforms between groups (DFU cases vs. diabetes controls vs. healthy controls) for both left and right limbs. Significance level for all *P*-value hypothesis testing was set at $P < 0.05$.

3. Results

3.1. Participant characteristics

A total of 99 participants were recruited from a larger study (Fernando et al., 2016c). This included 16 in the DFU cases, 50 in the diabetes controls and 33 in the healthy controls. The demographic, anthropometric characteristics and walking parameters of the three groups are reported in Table 1. The DFU group had a larger body mass, body mass index (BMI), waist circumference and lower cadence and gait speed compared to the two control groups ($P < 0.05$). The diabetes controls group had a larger body mass, BMI, waist circumference and lower cadence and gait speed compared to healthy controls ($P < 0.05$).

3.2. Gait joint coordination variability

There was no significant difference ($P > 0.05$) between the groups (DFU cases vs. diabetes controls vs. healthy controls) for any of the coupling angles (hip-knee, knee-ankle, hip-ankle) for either the right or left limb (Fig. 1).

3.3. Coupling pattern frequency

Left limb hip-knee coupling pattern frequency demonstrated only less anti-phase knee (hip ext./knee ext) in the diabetes controls vs. healthy controls ($P = 0.004$), with no difference between DFU cases vs. healthy controls ($P = 0.064$). There was more in-phase hip (hip extension/knee flexion) in DFU cases vs. healthy controls ($P = 0.047$) and between diabetes controls vs. healthy controls ($P = 0.018$) (Fig. 2A). Left limb knee-ankle coupling pattern frequency demonstrated more in-phase ankle (knee flexion/ankle plantarflexion) for DFU cases vs. healthy controls ($P = 0.007$) and for DFU cases vs. diabetes controls ($P = 0.010$) (Fig. 2B). Left limb hip-ankle coupling pattern frequency demonstrated more anti-phase ankle (hip extension/ankle dorsiflexion) for DFU cases vs. healthy controls ($P = 0.017$) and for DFU cases vs. diabetes controls ($P = 0.001$). There was more anti-phase hip (hip extension/ankle dorsiflexion) for the diabetes controls vs. healthy controls ($P = 0.003$) (Fig. 2C).

Right limb hip-knee coupling demonstrated no significant difference in pattern frequencies (Fig. 3A). Right knee-ankle coupling pattern frequency demonstrated more anti-phase ankle (knee extension/ankle plantarflexion) for the healthy controls vs. diabetes controls ($P = 0.018$) (Fig. 3B). Right limb hip-ankle coupling pattern frequency demonstrated less in-phase ankle (hip flexion/ankle dorsiflexion) for DFU cases vs. healthy controls ($P = 0.001$) and diabetes controls vs. healthy controls ($P = 0.007$). There was less anti-phase ankle (hip extension/ankle dorsiflexion) for diabetes controls vs. healthy controls ($P = 0.01$). There was more anti-phase hip (hip extension/ankle dorsiflexion) for DFU cases vs. healthy controls ($P = 0.039$) and diabetes controls vs. healthy controls ($P = 0.001$). Finally, there was more anti-phase hip (hip flexion/ankle plantarflexion) for DFU cases vs. healthy controls ($P < 0.001$) and for diabetes controls vs. healthy controls ($P = 0.002$).

Quantile regression analysis indicated that body mass and gait speed did not significantly influence coupling pattern frequency across the 25th, 50th, and 75th quantiles. These findings suggest that differences in coupling pattern frequency were consistent across the distribution, irrespective of variations in body mass and gait speed.

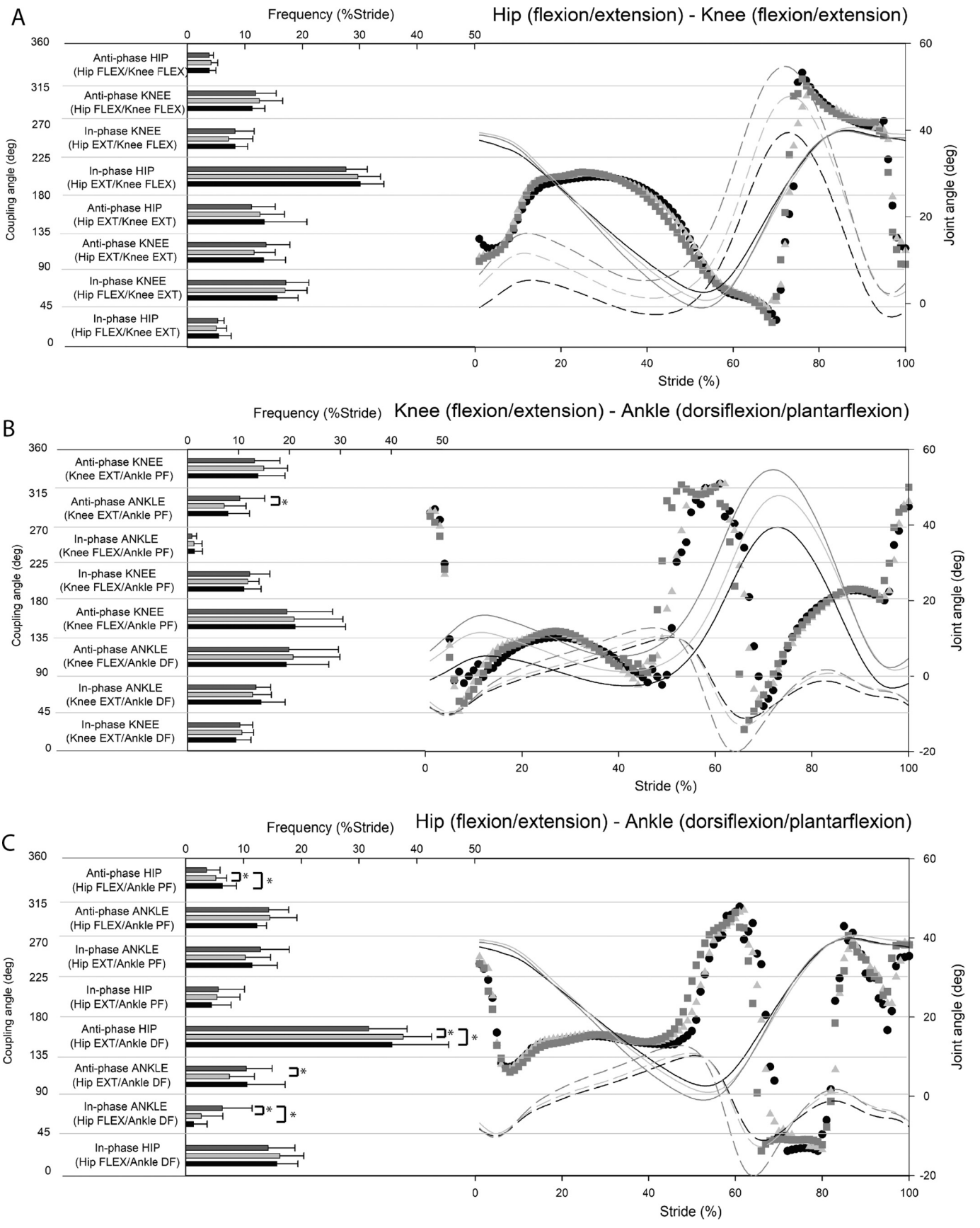

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Fig. 3. (A) Mean coupling angle for hip-knee coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – hip angle solid line; knee angle medium dash line), and pattern frequency (Y1 - bars) for the right stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. (B) Mean coupling angle for knee-ankle coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – knee angle solid line; ankle angle medium dash line), and pattern frequency (Y1 - bars) for the right stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. (C) Mean coupling angle for hip-ankle coupling angle (Y1 axis - scatter symbols), joint angles (Y2 axis – hip angle solid line; ankle angle medium dash line), and pattern frequency (Y1 - bars) for the right stride. DFU cases – black dots symbols, lines and bars; Diabetes controls – Grey triangles symbols, lines and bars; Healthy controls - Dark grey squares symbols, lines and bars. FLEX – Flexion; EXT – Extension; DF – Dorsiflexion; PF – Plantarflexion.

4. Discussion

This research was the first to our knowledge to investigate the lower limb gait joint coordination variability using the modified vector coding technique among individuals with DFU cases compared to individuals with type 2 diabetes without a history of DFUs and individuals without type 2 diabetes or a foot ulcer, revealing findings that warrant careful consideration. It was hypothesised that compared to controls, cases with DFUs would display reduced coordination variability measures during self-paced barefoot gait. This hypothesis was not supported, with no significant differences in gait joint coordination variability across DFU cases, diabetes controls, and healthy controls, but did reveal distinct coupling pattern frequency differences.

These findings build upon research that has only investigated linear measures of DFU gait (i.e. maximum, minimum and RoM values for lower limb joints during the gait cycle) (Fernando et al., 2016b) and suggest that, in terms of coordination variability, individuals with DFU cases do not display significant deviations from those with type 2 diabetes or healthy individuals. This prompts a re-evaluation of gait mechanics in the context of DFU, as focusing solely on single-point measures (e.g., maximum plantarflexion angle) provide limited insight into the complex coordination patterns that drive efficient movement.

Coordination variability is important because it reflects the interaction between muscle contractions and joint movements, which collectively generate ground reaction forces. Efficient gait relies on the synchronised activation of muscles across joints, allowing for the smooth transfer of forces to the ground. Kinematic variability, therefore serves as an indicator of underlying neuromuscular control strategies. While a certain level of variability can enhance adaptability in gait, too much or too little may impair the effective generation of ground reaction forces. It's important to distinguish between average patterns of coordination and stride-to-stride variability.

The observed differences in coupling pattern frequency between DFU cases, diabetes controls, and healthy controls provide important insights into the specific coordination challenges associated with diabetic foot ulcers. Notably, DFU cases demonstrated increased in-phase hip and knee coupling on the left limb, as well as greater in-phase coupling at the knee-ankle and hip-ankle joints, indicating a distinct shift in coordination dynamics compared to healthy controls. This prevalence of in-phase coupling suggests that individuals with DFU may exhibit a more synchronised but potentially rigid movement strategy, possibly as a compensatory mechanism for stability due to reduced sensory feedback from the feet. Additionally, the increased anti-phase coupling observed at the right limb's hip-ankle joint further highlights asymmetries that might reflect altered motor control or adaptive responses to underlying structural or neuropathic changes in these patients. These coordination adaptations could reduce gait flexibility, diminishing the ability to adjust to surface variations or unexpected perturbations, which is particularly concerning given the increased risk of ulceration and potential injury. Collectively, these findings underscore the importance of targeting specific joint coordination patterns in rehabilitation, as addressing such in-phase and anti-phase coupling tendencies might improve gait adaptability and reduce the biomechanical stressors that contribute to DFU progression.

While average coordination reflects the general movement strategy, coordination variability from stride to stride provides insight into how adaptable the gait system is in response to external or internal perturbations. Reduced variability could indicate rigidity or impaired adaptability, whereas excessive variability could suggest a lack of motor control (Bernstein, 1967; Dingwell et al., 1999a; Newell and Corcos, 1993). In this study, the nuanced differences in coupling frequency patterns, particularly in anti-phase movements, highlight the complexity of this issue. Further exploration of these distinctions, alongside the consideration of clinical factors like pain, fatigue, and neuropathy, is needed to better understand the biomechanical implications for individuals with DFUs.

While the currently study significantly contributes to the understanding of lower limb gait coordination in individuals with DFU, it is important to acknowledge certain limitations. Only the sagittal plane coordination variability was examined due to the potential risk of knee modelling using the Plug-in Gait model (Okahisa et al., 2023), more exploration research into the relationships between other axes of rotation needs to be undertaken. Additionally, individuals were able to walk at this self-selected pace. The lack of significant difference in coordination variability observed in this study might be due to the number of trials used to calculate the mean coupling angle. Research has varied anywhere from three (Samaan et al., 2022), five (Needham et al., 2020; Pelegrinelli et al., 2022), upwards to 10–11 (Miller et al., 2010; Wyatt et al., 2021) and 15 (Heiderscheit et al., 2002). The study by Hafer and Boyer (2017) is the only one to have examined the minimum number of strides required for reliable calculation of coordination variability using the modified vector coding technique in controlled-speed treadmill walking and running. Their findings indicate that 10 strides for walking and 8 strides for running yield reliable estimates. However, the authors note the need for further research to determine if these stride counts are equally applicable to self-paced, overground walking and running. Further research needs to examine the number of trials, force gait speed as a control parameter and the effect of fatigue/pain on coordination variability in this cohort.

5. Conclusions

In conclusion, the absence of significant differences in gait joint coordination variability among individuals with DFUs challenges the initial hypothesis that these individuals would exhibit reduced variability. This hypothesis was based on the assumption that DFUs, often associated with sensory impairments and muscle weakness, would limit the body's ability to adaptively coordinate joint movements, thereby reducing variability. However, the lack of significant findings suggests that DFU cases may maintain coordination variability similar to healthy individuals, possibly due to compensatory mechanisms.

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CRediT authorship contribution statement

Robert G. Crowther: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation,

Conceptualization. **Aaron Robertson:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Malindu E. Fernando:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Peter A. Lazzarini:** Writing – review & editing, Writing – original draft, Formal analysis. **Kunwarjit S. Sangla:** Writing – review & editing, Writing – original draft. **Jonathan Golledge:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known conflicts of interest.

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References

Aan de Stegge, W.B., Abu-Hanna, A., Bus, S.A., 2020. Development of a multivariable prediction model for plantar foot ulcer recurrence in high-risk people with diabetes. BMJ Open Diabetes Res. Care 8 (1). https://doi.org/10.1136/bmjdrc-2020-001207. Mar.

Armstrong, D.G., Boulton, A.J.M., Bus, S.A., 2017. Diabetic foot ulcers and their recurrence. N. Engl. J. Med. 376 (24), 2367–2375. https://doi.org/10.1056/NEJMra1615439. Jun 15.

Barn, R., Waaijman, R., Nollet, F., Woodburn, J., Bus, S.A., 2015. Predictors of barefoot plantar pressure during walking in patients with diabetes, peripheral neuropathy and a history of ulceration. PLoS One 10 (2), e0117443. https://doi.org/10.1371/journal.pone.0117443.

Bernstein, N.A., 1967. The Co-Ordination and Regulation of Movements. Pergamon Press.

Bus, S.A., Armstrong, D.G., Crews, R.T., Gooday, C., Jarl, G., Kirketerp-Moller, K., Viswanathan, V., Lazzarini, P.A., 2024a. Guidelines on offloading foot ulcers in persons with diabetes (IWGDF 2023 update). Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3647 e3647. Mar.

Bus, S.A., Sacco, I.C.N., Monteiro-Soares, M., Raspovic, A., Paton, J., Rasmussen, A., Lavery, L.A., van Netten, J.J., 2024b. Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2023 update). Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3651 e3651. Mar.

Byrnes, J., Ward, L., Jensen, S., Sagoo, M., Charles, D., Mann, R., Nghiem, S., Finch, J., Gavaghan, B., McBride, L.J., Lazzarini, P.A., 2024. Health-related quality of life in people with different diabetes-related foot ulcer health states: a cross-sectional study of healed, non-infected, infected, hospitalised and amputated ulcer states. Diabetes Res. Clin. Pract. 207. https://doi.org/10.1016/j.diabres.2023.111061, 111061. Jan.

Chang, R., Van Emmerik, R., Hamill, J., 2008. Quantifying rearfoot-forefoot coordination in human walking. J. Biomech. 41 (14), 3101–3105. https://doi.org/10.1016/j.jbiomech.2008.07.024. Oct 20.

Chuter, V.H., Spink, M.J., David, M., Lanting, S., Searle, A., 2012. Clinical foot measurements as a proxy for plantar pressure testing in people with diabetes. J. Foot Ankle Res. 14 (56). https://doi.org/10.1186/s13047-021-00494-4.

Dingwell, J.B., Cusumano, J.P., Sternad, D., Cavanagh, P.R., 1999a. Stride-to-stride variability in human walking is not noise. In: Proceedings of The 23rd Annual Meeting of the American Society of Biomechanics. University of Pittsburgh, Pittsburgh Pennsylvania, pp. 58–59.

Dingwell, J.B., Ulbrecht, J.S., Boch, J., Becker, M.B., O'Gorman, J.T., Cavanagh, P.R., 1999b. Neuropathic gait shows only trends towards increased variability of sagittal plane kinematics during treadmill locomotion. Gait Posture 10 (1), 21–29. Sep. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=10469938.

Fernando, D.J., Masson, E.A., Veves, A., Boulton, A.J., 1991. Relationship of limited joint mobility to abnormal foot pressures and diabetic foot ulceration. Diabetes Care 14 (1), 8–11. https://doi.org/10.2337/diacare.14.1.8. Jan.

Fernando, M.E., Crowther, R.G., Lazzarini, P.A., Sangla, K., Cunningham, M., Buttner, P., Golledge, J., 2013. Biomechanical characteristics of peripheral diabetic neuropathy: a systematic review and meta-analysis of findings from the gait cycle, muscle activity and dynamic barefoot plantar pressure. Clin Biomech (Bristol, Avon) 28 (8), 831–845. https://doi.org/10.1016/j.clinbiomech.2013.08.004. Oct.

Fernando, M.E., Crowther, R.G., Pappas, E., Lazzarini, P., Cunningham, M., Sangla, K., Buttner, P., Golledge, J., 2014. Plantar pressure in diabetic peripheral neuropathy patients with active foot ulceration, previous ulceration, and no history of ulceration: a meta-analysis of observational studies. PLoS One 9 (6), e99050. https://doi.org/10.1371/journal.pone.0099050.

Fernando, M.E., Crowther, R.G., Cunningham, M., Lazzarini, P.A., Sangla, K.S., Golledge, J., 2015. Lower limb biomechanical characteristics of patients with neuropathic diabetic foot ulcers: the diabetes foot ulcer study protocol. BMC Endocr. Disord. 15, 59. https://doi.org/10.1186/s12902-015-0057-7. Oct 23.

Fernando, M., Crowther, R.G., Cunningham, M., Lazzarini, P.A., Sangla, K.S., Buttner, P., Golledge, J., 2016a. The reproducibility of acquiring three dimensional gait and plantar pressure data using established protocols in participants with and without type 2 diabetes and foot ulcers. J Foot Ankle Res 9, 4. https://doi.org/10.1186/s13047-016-0135-8.

Fernando, M.E., Crowther, R.G., Lazzarini, P.A., Sangla, K.S., Buttner, P., Golledge, J., 2016b. Gait parameters of people with diabetes-related neuropathic plantar foot ulcers. Clin. Biomech. (Bristol Avon) 37, 98–107. https://doi.org/10.1016/j.clinbiomech.2016.06.006. Aug.

Fernando, M.E., Crowther, R.G., Lazzarini, P.A., Sangla, K.S., Wearing, S., Buttner, P., Golledge, J., 2016c. Plantar pressures are higher in cases with diabetic foot ulcers compared to controls despite a longer stance phase duration. BMC Endocr. Disord. 16 (1), 51. https://doi.org/10.1186/s12902-016-0131-9. , Sep 15.

Fernando, M.E., Crowther, R.G., Lazzarini, P.A., Yogakanthi, S., Sangla, K.S., Buttner, P., Jones, R., Golledge, J., 2017. Plantar pressures are elevated in people with longstanding diabetes-related foot ulcers during follow-up. PLoS One 12 (8), e0181916. https://doi.org/10.1371/journal.pone.0181916.

Fernando, M.E., Crowther, R.G., Lazzarini, P.A., Sangla, K.S., Wearing, S., Buttner, P., Golledge, J., 2019. Gait in people with nonhealing diabetes-related plantar ulcers. Phys. Ther. 99 (12), 1602–1615. https://doi.org/10.1093/ptj/pzz119. , Dec 16.

Fernando, M.E., Horsley, M., Jones, S., Martin, B., Nube, V.L., Charles, J., Cheney, J., Lazzarini, P.A., Australian Diabetes-related Foot Disease, G., & Pathways, P, 2022. Australian guideline on offloading treatment for foot ulcers: part of the 2021 Australian evidence-based guidelines for diabetes-related foot disease. J Foot Ankle Res 15 (1), 31. https://doi.org/10.1186/s13047-022-00538-3. May 5.

Formosa, C., Gatt, A., Chockalingam, N., 2013. The importance of clinical biomechanical assessment of foot deformity and joint mobility in people living with type-2 diabetes within a primary care setting. Prim. Care Diabetes 7 (1), 45–50. https://doi.org/10.1016/j.pcd.2012.12.003. Apr.

Hafer, J.F., Boyer, K.A., 2017. Variability of segment coordination using a vector coding technique: reliability analysis for treadmill walking and running. Gait Posture 51, 222–227. https://doi.org/10.1016/j.gaitpost.2016.11.004. Jan.

Hamill, J., Haddad, J.M., Mcdermott, W.J., 2000. Issues in quantifying variability from a dynamical system perspective. J. Appl. Biomech. 16, 407–418.

Heiderscheit, B.C., Hamill, J., van Emmerik, E.A., 2002. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. J. Appl. Biomech. 18 (2), 110–121. http://www.humankinetics.com/.

Huang, C.H., James, K., Lanois, C., Corrigan, P., Yen, S.C., Stefanik, J., 2023. Inter-joint coordination variability is associated with pain severity and joint loading in persons with knee osteoarthritis. J. Orthop. Res. 41 (12), 2610–2616. https://doi.org/10.1002/jor.25592. Dec.

Kanade, R.V., van Deursen, R.W., Harding, K., Price, P., 2006. Walking performance in people with diabetic neuropathy: benefits and threats. Diabetologia 49 (8), 1747–1754. https://doi.org/10.1007/s00125-006-0309-1. Aug.

Lazzarini, P.A., Crews, R.T., van Netten, J.J., Bus, S.A., Fernando, M.E., Chadwick, P.J., Najafi, B., 2019. Measuring plantar tissue stress in people with diabetic peripheral neuropathy: a critical concept in diabetic foot management. J. Diabetes Sci. Technol. 13 (5), 869–880. https://doi.org/10.1177/1932296819849092. , Sep.

Lazzarini, P.A., Cramb, S.M., Golledge, J., Morton, J.I., Magliano, D.J., Van Netten, J.J., 2023a. Global trends in the incidence of hospital admissions for diabetes-related foot disease and amputations: a review of national rates in the 21st century. Diabetologia 66 (2), 267–287. https://doi.org/10.1007/s00125-022-05845-9. Feb.

Lazzarini, P.A., Raspovic, A., Prentice, J., Commons, R.J., Fitridge, R.A., Charles, J., Cheney, J., Purcell, N., Twigg, S.M., 2023b. Australian evidence-based guidelines for the prevention and management of diabetes-related foot disease: a guideline summary. Med. J. Aust. 219 (10), 485–495. https://doi.org/10.5694/mja2.52136. Nov 20.

Lazzarini, P.A., Armstrong, D.G., Crews, R.T., Gooday, C., Jarl, G., Kirketerp-Moller, K., Viswanathan, V., Bus, S.A., 2024a. Effectiveness of offloading interventions for people with diabetes-related foot ulcers: a systematic review and meta-analysis. Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3650 e3650. Mar.

Lazzarini, P.A., Raspovic, K.M., Meloni, M., van Netten, J.J., 2024b. A new declaration for feet's sake: halving the global diabetic foot disease burden from 2% to 1% with next generation care. Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3747 e3747. Mar.

Miller, R.H., Chang, R., Baird, J.L., Van Emmerik, R.E., Hamill, J., 2010. Variability in kinematic coupling assessed by vector coding and continuous relative phase. J. Biomech. 43 (13), 2554–2560. https://doi.org/10.1016/j.jbiomech.2010.05.014. Sep 17.

Mueller, M.J., Minor, S.D., Sahrmann, S.A., Schaaf, J.A., Strube, M.J., 1994. Differences in the gait characteristics of patients with diabetes and peripheral neuropathy compared with age-matched controls. Phys. Ther. 74 (4), 299–308. Apr. discussion 309-213. https://doi.org/10.1093/ptj/74.4.299.

Needham, R.A., Naemi, R., Chockalingam, N., 2015. A new coordination pattern classification to assess gait kinematics when utilising a modified vector coding technique. J. Biomech. 48 (12), 3506–3511. https://doi.org/10.1016/j.jbiomech.2015.07.023. Sep 18.

Needham, R.A., Naemi, R., Hamill, J., Chockalingam, N., 2020. Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding. Foot (Edinb.) 44. https://doi.org/10.1016/j.foot.2020.101678, 101678. Sep.

Newell, K.M., Corcos, D.M., 1993. Issues in variability and motor control. In: Newell, K. M., Corcos, D.M. (Eds.), Variability and Motor Control. Human Kinetics, pp. 1–12.

Okahisa, T., Matsuura, T., Tomonari, K., Komatsu, K., Yokoyama, K., Iwase, J., Yamada, M., Sairyo, K., 2023. Between-day reliability and minimum detectable change of the conventional gait model 2 and plug-in gait model during running. Gait Posture 100, 171–178. https://doi.org/10.1016/j.gaitpost.2022.12.006. Feb.

Pelegrinelli, A.R.M., Kowalski, E., Ryan, N.S., Moura, F.A., Lamontagne, M., 2022. Lower limb inter-joint coordination in individuals with osteoarthritis before and after a total knee arthroplasty. Clin. Biomech. 100. https://doi.org/10.1016/j.clinbiomech.2022.105806.

Pop-Busui, R., Boulton, A.J., Feldman, E.L., Bril, V., Freeman, R., Malik, R.A., Sosenko, J. M., Ziegler, D., 2017. Diabetic neuropathy: a position statement by the American Diabetes Association. Diabetes Care 40 (1), 136–154. https://doi.org/10.2337/dc16-2042. Aug.

Raspovic, A., 2013. Gait characteristics of people with diabetes-related peripheral neuropathy, with and without a history of ulceration. Gait Posture 38 (4), 723–728. https://doi.org/10.1016/j.gaitpost.2013.03.009. Sep.

Samaan, M.A., Pedoia, V., Tanaka, M.S., Souza, R.B., Benjamin Ma, C., Li, X., 2022. Hip-knee joint coordination patterns are associated with patellofemoral joint cartilage composition in patients with anterior cruciate ligament reconstruction. J. Appl. Biomech. 38 (1), 20–28. https://doi.org/10.1123/jab.2021-0111. Feb 1.

Schaper, N.C., van Netten, J.J., Apelqvist, J., Bus, S.A., Fitridge, R., Game, F., Monteiro-Soares, M., Senneville, E., Board, I.E., 2024. Practical guidelines on the prevention and management of diabetes-related foot disease (IWGDF 2023 update). Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3657 e3657. Mar.

Sparrow, W.A., Donavan, E., van Emmerik, R., Barry, E.B., 1987. Using relative motion plots to measure changes in intra-limb and inter-limb coordination. J. Mot. Behav. 19 (1), 115–129.

Takabayashi, T., Edama, M., Inai, T., Kubo, M., 2023. Differences in the coordination and its variability among foot joints during running in neutral foot and flatfoot. Scand. J. Med. Sci. Sports 33 (3), 235–245. https://doi.org/10.1111/sms.14267. Mar.

van Netten, J.J., Raspovic, A., Lavery, L.A., Monteiro-Soares, M., Paton, J., Rasmussen, A., Sacco, I.C.N., Bus, S.A., 2024. Prevention of foot ulcers in persons with diabetes at risk of ulceration: a systematic review and meta-analysis. Diabetes Metab. Res. Rev. 40 (3). https://doi.org/10.1002/dmrr.3652 e3652. Mar.

Veves, A., Murray, H.J., Young, M.J., Boulton, A.J., 1992. The risk of foot ulceration in diabetic patients with high foot pressure: a prospective study. Diabetologia 35 (7), 660–663. https://doi.org/10.1007/BF00400259. Jul.

Wukich, D.K., Raspovic, K.M., 2018. Assessing health-related quality of life in patients with diabetic foot disease: why is it important and how can we improve? The 2017 Roger E. Pecoraro award lecture. Diabetes Care 41 (3), 391–397. https://doi.org/10.2337/dci17-0029. Mar.

Wyatt, H., Wier, G., Jewell, C., van Emmerik, R., J, H., 2021. Stable coordination variability in overground walking and running at preferred and fixed speeds. J. Appl. Biomech. 37 (4), 299–303. https://doi.org/10.1123/jab.2020-0368.

Zhang, Y., Lazzarini, P.A., McPhail, S.M., van Netten, J.J., Armstrong, D.G., Pacella, R.E., 2020. Global disability burdens of diabetes-related lower-extremity complications in 1990 and 2016. Diabetes Care 43 (5), 964–974. https://doi.org/10.2337/dc19-1614. May.