

Research Article

Static and Dynamic Predictors of Foot Progression Angle in Individuals with and without Diabetes Mellitus and Peripheral Neuropathy

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Abstract

Introduction: Foot progression angle (FPA) is a predictor of elevated regional plantar stresses and loads, which are indicators of dermal injury risk in individuals with diabetes mellitus and peripheral neuropathy (DMPN). FPA accounts for 15-45% of the variance in plantar stresses and loads in adults with DMPN. However, the biomechanical factors underlying an "out-toeing" gait pattern in this clinical population have not been examined. The primary purpose of this study was to identify static and dynamic predictors of foot progression angle magnitude in adults with and without DMPN.

Methods: Thirty-three adults with and 12 adults without diabetes mellitus participated. Hip rotation, ankle dorsiflexion, and resting calcaneal stance position were measured using a standard goniometer. Kinematic and kinetic data were collected during walking.

Results and Discussion: Static predictor variables did not significantly predict foot progression angle magnitude using multiple regression analysis. Of the dynamic predictor variables, thigh and shank lateral rotation accounted for 37% of foot progression angle variance ($p < .01$).

Conclusions: Our results show that dynamic measures of external rotation of proximal segments (thigh, shank) during gait are strong predictors of foot progression angle. Static measures of limited joint mobility and joint position do not predict foot progression angle. These findings suggest that targeting the thigh and shank rotation using verbal or tactile cueing may be a potential strategy when trying to alter walking movement patterns towards decreasing external (lateral) FPA to minimize risk of elevated regional plantar stresses in adults with DMPN at risk for ulceration.

ABBREVIATIONS

DMPN: Diabetes Mellitus and Peripheral Neuropathy; FPA: Foot Progression Angle; NPU: Neuropathic Plantar Ulcer; VPT: Vibration Perception Threshold

INTRODUCTION

Elevated plantar stresses and loads are an indicators of skin injury risk in adults with diabetes mellitus and peripheral neuropathy (DMPN), and are thought to initiate a transition to

neuropathic plantar ulcer (NPU) development and non-traumatic lower extremity amputation [1,2]. Up to 25% of individuals with DMPN have a lifetime risk of developing NPUs [3,4]. Further, more than 65,000 non-traumatic lower extremity amputations in adults with DMPN are done annually in the United States, with 84% having been preceded by the development of a NPU [5,6]. Therefore, the development and recurrence of NPUs in DMPN represent a significant healthcare burden.

Foot progression angle (FPA), or "toe-out angle" has been implicated in a myriad of lower extremity musculoskeletal

conditions [1,7-9]. Indeed, external FPA magnitude (or “out-toeing”) is greater in individuals with DMPN, and is a noted predictor of plantar stresses and loads in foot regions vulnerable to NPU development in adults with DMPN [1,2,7,10]. It has been posited that an “out-toeing” gait may contribute to the progression of osseoligamentous deformities of the forefoot (e.g., hammer toe) and medial longitudinal arch (calcaneus, talus, navicular, medial and middle cuneiforms, and the 1st and 2nd metatarsal bones and ligamentous network) through repetitive loading, thereby increasing the magnitude and duration of stresses and loads on the skin of medial plantar surface [7,11]. In support, FPA accounts for 15-45% of the variance of forefoot peak plantar pressure [1] and medial column loading [7] in adults with DMPN. However, the biomechanical factors underlying an “out-toeing” gait pattern in this clinical population have not been examined. Recently, FPA modification has been proposed as a potential rehabilitative strategy for the reduction of regional plantar stresses and loads [12]. Induced FPA reduction of at least 25° (“in-toeing”) resulted in significant decreases in forefoot and midfoot peak plantar pressures in healthy participants [12]. Thus, it would be prudent to investigate the key characteristics of FPA magnitude to assist clinicians with identifying and addressing specific impairments that could prevent achieving the amount of “in-toeing” necessary to have the desired therapeutic effect of minimizing the increased plantar stresses and subsequent plantar skin breakdown associated with increased FPA in adults with DMPN.

A combination of movement impairments of the foot and ankle influences the magnitude and duration of plantar stresses and loads in adults with DMPN. Many have cited reductions in 1st metatarsophalangeal joint (1st MTPJ) extension [1,13,14], ankle dorsiflexion [15-19], and hip and thigh rotation [20,21] as lower extremity movement impairments in DMPN. Of these, 1st metatarsophalangeal joint (MTPJ) and ankle joint range of motion are significant static and dynamic predictors of forefoot peak plantar pressure in participants with DMPN with a prior history of NPU [1,14,18,19,22]. Similarly, the natural adoption of an “out-toeing” gait pattern could arise from a cluster of structural and alignment factors [23]. Svenningsen and colleagues [24] showed that passive hip rotation, measured goniometrically, was associated with internal FPA (“in-toeing”) magnitude in healthy study participants. Others have shown that segmental rotation and torsion of the thigh and shank are moderately associated with FPA in different clinical populations, though these findings remain somewhat controversial [23,25,26]. Interestingly, specific mechanistic biomechanical factors that contribute to FPA in individuals with DMPN have not been identified despite of the significant association between FPA magnitude and increases in regional plantar stresses and loads.

Therefore, the purposes of this study were to: 1) determine static and dynamic predictors of FPA in individuals with and without DMPN, and 2) determine group differences in FPA and in select lower extremity static and dynamic measures of foot, ankle, and hip motion. We hypothesized that, using multiple regression analyses, goniometric measurement of ankle dorsiflexion motion, segmental rotation of the thigh during walking, and group assignment (based on disease severity) would explain a significant portion of the variance in FPA. In addition, we

hypothesized that participants with DMPN would have greater FPA magnitude, lower static measures of ankle dorsiflexion and hip joint rotation ranges of motion, and less segmental rotation of the thigh and shank during gait compared to participants with DM and healthy controls.

MATERIALS AND METHODS

Participants

Forty-five participants with and without diabetes were studied, and provided written informed consent as approved by the university Institutional Review Board. Participants were assigned to one of four groups as previously described: 1) age-matched healthy control (CON, n=12), 2) diabetes mellitus without peripheral neuropathy (DM, n=12), 3) diabetes mellitus and peripheral neuropathy without a prior history of a neuropathic plantar ulcer (DMPN-NPU, n=11), and 4) diabetes mellitus and peripheral neuropathy with a prior history of a neuropathic plantar ulcer (DMPN+NPU, n=10) [27]. Peripheral neuropathy classification determined as previously described [27]. Participants in the DMPN+NPU group reported having had a prior ulcer on one or both feet (8 unilateral, 2 bilateral). Participants classified as DMPN+NPU reporting a history of bilateral ulceration were included so as not to narrow the pool of available participants for that group. Participants in the DMPN+NPU group reported having NPUs in the following areas: 5 in the forefoot, 2 in the midfoot, and 3 in the hindfoot. Participants classified as DMPN+NPU were not ulcerated at the time of testing. Those identified as non-ambulatory or with lower extremity amputations proximal to the digits were excluded from the study.

Static predictors

Data collection: Static predictors in this investigation were operationally defined as goniometric measures of position and excursion of select lower extremity joints. Hip (coxafemoral) joint internal (medial) and external (lateral) rotation were measured using a bubble inclinometer (Medical Research Ltd, Leeds LS124JF, United Kingdom) with a precision of 1° using the methods described by Ellison et al. [28]. The reported intra-rater reliability for hip internal and external rotation measurement using the procedures outlined by Ellison et al., range from 0.95-0.99 in both directions in subjects with and without low back pain dysfunction [28]. Total hip rotation range of motion is the sum of hip internal rotation and hip external rotation. Ankle joint dorsiflexion was measured in prone lying using a standard goniometer using previously described procedures with a precision of 2° [29]. Measurement of ankle joint dorsiflexion was performed with the subtalar joint held in palpated neutral alignment while the calcaneus moved into dorsiflexion. The axis of the goniometer was aligned with the lateral malleolus, the moveable arm aligned with the axis of the lateral malleolus and fibular head. In this position, the stationary arm was aligned with the fifth ray [29]. The reported intra-rater reliability for ankle joint ROM measurement using the procedures outlined by Diamond et al. [29], ranges from .89-.96. Resting calcaneal stance position (RSCP), a goniometric weight bearing measurement of calcaneal position in the frontal plane, was obtained using modified measurement procedures described by Picciano et al.

[30]. Using a water-soluble marker, a line of bisection of the lower one-third of the leg was drawn. In a similar fashion, a line was drawn between the lateral and medial malleoli representing a bisection of the calcaneus. RCSP was the measured angle formed between the lines of the bisection of the posterior calcaneus and the floor (horizontal) using a standard 2° goniometer [30].

Dynamic predictors

Data collection: Dynamic predictors in this investigation were operationally defined as lower extremity segmental and inter-segmental positions and orientations at select points during the stance phase of gait. Three-dimensional kinematic data were collected during gait for the pelvis and bilateral lower extremities while participants walked at a self-selected speed over a 4 m distance. Kinematic data were acquired using an infrared 8-camera, 200 Hz motion capture system (Vicon MX, Los Angeles, CA, USA). Cameras and force plates were calibrated prior to each kinematic data collection.

Marker placement: All participants were fitted with 10 mm diameter retro-reflective markers affixed directly to the skin or to pre-molded rigid plate in a non-collinear arrangement to establish segment coordinate systems for the foot, shank, thigh, and pelvis. A modification of the “obesity-specific marker set”, described by Lerner et al., for the trunk, pelvis, and thigh, was used in this study in an effort to account for potential motion artifact secondary to trunk and pelvic adiposity [31,32]. Markers on the pelvis included single markers on the right and left posterior superior iliac spines, with an accompanying marker cluster placed on the sacrum. Marker clusters on the pelvis have been shown to have greater repeatability and less movement variability during non-sagittal plane motion of the pelvis in overweight and obese individuals [33]. To correct for marker displacement secondary to trunk and pelvic adiposity, digitized markers were created for the anterior superior iliac spines and iliac crests with a static digitizing wand (C-Motion, Germantown, MD) using procedures described by Lerner et al [31,32]. Additional corrections were made using measurements of inter-ASIS distance using skinfold caliper in subject-specific models. Lerner et al. [31], reported that use of marker clusters and digitized markers on the thigh and pelvis minimized overestimation of lower extremity kinematics and kinetics. Single thigh markers were placed proximally on the greater trochanter and distally on the medial and lateral femoral epicondyles, with a 4-marker cluster for tracking on the distal thigh superior to the lateral epicondyle. We utilized a marker configuration for the foot and shank described by Carson et al. [34], and by Hastings et al. [35], which included a single, rigid body foot segment. Individual shank markers were placed on the fibular head, tibial tuberosity, and malleoli, with a 4-marker cluster placed on the distal shank superior to the lateral malleolus. The hindfoot segment was defined by calcaneal marker placement on the sustentaculum tali, fibular trochlea, and by two mounted markers on a molded plastic plate applied to the posterior calcaneal bisection [35]. The forefoot segment was defined markers placed at the midpoint between the second and third metatarsal heads, at the first and fifth metatarsal heads, and bases of the first and fifth metatarsals. The hallux segment was defined by a plate with three mounted markers. The proximal and distal markers were aligned parallel with the long axis of the

proximal phalanx of the hallux [35]. Participants were asked to walk barefoot at a self-selected speed. All were given at least 1-2 practice trials prior to recording. To minimize risks associated with barefoot walking in participants in the DMPN groups, walking distance was truncated to include the steps during which kinematic variables were measured. Walking speed was calculated for the stride during which kinematic variables were measured [35]. A minimum of five trials in which participants were able to complete one stride were collected. A minimum of three trials were included in the analysis if walking speed was within one standard deviation of the within-trial mean for each participant to account for the influence of walking speed on the magnitude of lower extremity kinematics in individuals classified as obese [32,36].

Data processing and statistical analysis

Kinematic and kinetic variables: All marker trajectories were processed using a fourth-order, low-pass filter set at 6 Hz in Visual 3D software (C-Motion, Inc, Rockville, MD). Inter-segmental and global orientation angles were derived using Cardan angle sequences, and parallel alignment of the segmental axes represent neutral position [35]. The primary kinematic variables were thigh rotation, shank rotation, hindfoot on shank sagittal (dorsiflexion/plantarflexion) and frontal (inversion/eversion) plane motion, and forefoot on hindfoot sagittal (dorsiflexion/plantarflexion) and transverse (abduction/adduction) plane motion. Foot progression angle was the value of transverse plane rotation of the foot segment around the local superior-inferior axis at the midstance of the gait cycle (i.e., 50% of the stance phase of walking) [37].

Group comparisons: Prior to all analyses, we conducted the Shapiro-Wilk test of normality to verify that continuous data for all variables were normally distributed [38]. The proportion of right versus left feet grouped as High FPA and Low FPA was assessed using Chi-square analysis. For all participants, the foot with the greater FPA magnitude was classified as High FPA and included in the multiple regression analysis. Based on previous work investigating asymmetry in lower extremity variables during gait, we also initially performed a two-way analysis of variance (Group [4 levels] X Side [2 levels]) to determine the main and interaction effects of group and side [39,40]. We then quantified the degree of inter-limb asymmetry (FPA Difference) by taking the absolute value of the difference in FPA magnitude between the High and Low FPA feet (|High-Low|), and performed a univariate analysis of variance to determine group differences in this measure. Based on previous work, the criterion for having a clinically meaningful measure of FPA Diff have reported degrees of asymmetry was 4° [41,42]. All static and dynamic predictor variables for the High FPA foot were analyzed using a univariate analysis of variance (ANOVA) to determine group differences. This analysis was performed to determine if group assignment should be included into a multiple regression analyses for both static and dynamic predictor variables. Post-hoc analyses were conducted using a Bonferroni correction, with statistical significance for all analyses set at $p < .05$. Statistical analyses were performed using IBM SPSS Statistics software, version 21.0 (SPSS Inc, Chicago, IL, USA).

Multiple regression analyses: The following multiple

regression analyses were conducted for all study participants, and were used to identify those static and dynamic variables most associated with FPA. Static variables were included based on a reasonable and statistical relationship with FPA and because static variables could be easily measured in the clinic. Dynamic variables also were included based on their possible relationship contributing to FPA, although these variables would be more difficult to measure clinically than the static variables. Understanding which predictors were most related to FPA may help to target intervention to reduce excessive FPA and associated negative complications (elevated plantar pressures and skin breakdown).

Multiple regression model of static (goniometric) predictors: Correlations between all static predictor variables and FPA (dependent variable) on the High FPA foot were analyzed using Pearson product moment correlation (*r*) [1,38]. Three candidate static predictor variables plus group dummy variables were selected for inclusion into a multiple regression analysis based on group differences in and bivariate correlational analyses of these variables with FPA. The static predictor variables entered into the final model were total hip rotation range of motion, ankle joint range of motion, and RSCP. Order for model entry for the static predictor variables was based on the proximal to distal location of the joint in the lower extremity.

Multiple regression models of dynamic (gait kinematic) predictors: A multiple regression analysis was performed on the dynamic predictor variables for the High FPA foot. Dynamic model predictor variables were determined a priori based on previously reported relationships between lower extremity movement impairments, FPA, and peak plantar pressure in adults with DMPN [1,14,18,19,23,26]. Correlations between four candidate dynamic predictor variables of FPA on the High FPA foot were analyzed using Pearson product moment correlation coefficient (*r*) [1,38]. Four candidate static predictor variables plus group dummy variables were selected for inclusion into a multiple regression analysis based on group differences in and

bivariate correlational analyses of these variables with FPA. The dynamic predictor variables measured at midstance were thigh relative to lab lateral rotation, shank relative to lab lateral rotation, hindfoot (calcaneus) relative to shank eversion, and forefoot relative to hindfoot abduction. The rationale for the inclusion of the hindfoot relative to shank eversion and forefoot relative to hindfoot abduction into the multiple regression analysis was to determine the unique contributions of inter-segmental foot motion during walking to FPA. Order for model entry for dynamic predictor variables was based on the proximal to distal location of the joint in the lower extremity.

RESULTS AND DISCUSSION

Results

Participant characteristics: Participant demographics are summarized in Table (1) [mean and standard deviation (SD)]. There were no group differences in age or height between groups. The CON and DM groups had a significantly lower body mass index (BMI) than the DMPN groups, but were not different from each other. The DMPN+NPU group had been diagnosed with diabetes earlier than the other diabetes groups. The DMPN groups had a significantly greater vibration perception threshold (VPT) than the DM and CON groups. There were no group differences in the proportion of right versus left feet that were classified as High FPA ($\chi^2=0.25$, *df* = 2, *p*=0.88).

Group comparisons: Means and standard deviation values for the static (goniometric), FPA, and dynamic (gait kinematic) variables are summarized in Table (2). The DMPN+NPU group had less total hip rotation range of motion, measured goniometrically, than the other participant groups. There were no group differences in range of motion or position for the other static predictor variables. There were main effects of side (High versus Low, *P*=0.03) and group (*P*=0.04). Post hoc pairwise comparisons showed that the DMPN+NPU group had a significantly greater High FPA than the DMPN-NPU group. There was no interaction effect of group x side (*p*=.76). The time series

Table 1: Participant characteristics.

	CON (N=12)	DM (N=12)	DMPN-NPU (N=11)	DMPN+NPU(n=10)	<i>P</i>
Age(years)	60(12)	58(9)	63(11)	58(11)	0.80
Height(m)	1.7(0.1)	1.7(0.1)	1.7(0.1)	1.7(0.1)	0.79
Sex(M:F)	7:5	5:7	4:7	5:5	0.95
BMI (kg/m²)	33 (5) [†]	34(8) [#]	39(9)	41(9)	0.08
Disease duration (years)	N/A	8(5) [#]	11 (9) [§]	24(8)	<0.01
Great Toe VPT(Volts)	20 (9) [†]	15 (6) [#]	37(11)	34(17)	<0.01
Walking Speed(m/s)	1.1(0.1)	1.1(0.1)	1.1(0.1)	1.1(0.1)	0.80
Side of greater FPA(Right: Left)	11R:1L	9R:3L	9R:3L	6R:4L	0.88

Values are expressed in mean (SD). Reported significance values are for overall group comparisons (*P*). †, #, §:significance values for group differences. BMI:†CON vs DMPN-NPU and DMPN+NPU;#:DM vs DMPN-NPU and DMPN+NPU; Disease duration(years):#DM vs DMPN+NPU, *P*<0.01; §DMPN-NPU vs DMPN+NPU, *P*<0.01.

Great Toe VPT: †CON vs DMPN-NPU/DMPN+NPU, *P*<0.01; #DM vs DMPN-NPU/DMPN+NPU, *P*<0.01

Abbreviations: VPT: Vibration Perception Threshold; FPA: Foot Progression Angle; BMI: Body Mass Index; CON: Healthy Control Participants DM: Participants with Diabetes Mellitus without Peripheral Neuropathy Participants; DMPN-NPU: Diabetes Mellitus and Peripheral Neuropathy without a prior history of a Neuropathic Plantar Ulcer; DMPN+NPU: Diabetes Mellitus and Peripheral Neuropathy with a prior history of Neuropathic Plantar Ulcer

Table 2: Static (goniometric) and dynamic (gaitkinematic) measures for the foot with the greater foot progression angle (High FPA).

Static variables	CON(n=12)	DM(n=12)	DMPN-NPU(n=11)	DMPN+NPU(n=10)	P
Total hip rotation ROM(deg)	77(19)	80(12)	69(16)	58(17)§	0.01
Ankle dorsiflexion ROM(deg)	8(5)	9(5)	8(4)	5(4)	0.20
RCSP(deg)	4(2)	2(4)	4(5)	4(5)	0.78
Dynamic variables					
High FPA(deg)	-15(6)	-14(5)	-13(7)§	-21(5)	0.03
Low FPA(deg)	-9(5)	-10(5)	-9(5)	-15(9)§	0.07
FPA Difference (High-Low)	6(4)	3(7)	5(4)	6(6)	0.76
Thigh relative to lab rotation(deg)	-1(9)	-6(9)	-4(13)	-9(7)	0.30
Shank relative to lab rotation(deg)	-4(13)	-8(9)	-9(14)	-16(8)	0.17
Hindfoot relative to Shank eversion(deg)	-7(9)	-4(6)	-6(6)	-2(5)	0.22
Forefoot relative to Hindfoot abduction(deg)	-6(7)	-3(6)	-3(9)	-5(8)	0.71
Walking speed(m/s)	1.1(0.1)	1.1(0.1)	1.1(0.1)	1.0(0.4)	0.74

Values are expressed in degrees, mean (SD). Reported significance values are overall group comparisons (P), §: significance values for group differences. High FPA: §DMPN-NPU vs DMPN+NPU, P=0.03. Total hip rotation: §CON vs DMPN+NPU, P=0.03; DM vs DMPN+NPU, P=0.01.

Abbreviations: Total hip rotation ROM: The Sum of Goniometric Measurement of Hip Internal (medial) and External (lateral) Rotation range of Motion in Pronelying; Ankle dorsiflexion ROM: Goniometric Ankle Dorsiflexion range of Motion Measurement in Pronelying; Resting Calcaneal Stance Position (RCSP): Goniometric Measure of Frontal Planecal Canoeal Position Relative to the Floor in Standing; High FPA: Foot with the Greater Foot Progression Angle Magnitude at Midstance, (-) =toe-out angle; Low FPA: Foot with the Greater Foot Progression Angle Magnitude at Midstance, (-) =toe-out angle; FPA Difference: the Absolute Value of the Difference in FPA Magnitude between the High and Low FPA Feet; Thigh relative to lab rotation: Thigh Segment to Lab External Rotation (-) Value at Midstance; Shank Relative to Lab Rotation: Shanks Segment to Lab External(-) Rotation Value at Midstance; Hindfoot Relative to Shank Eversion: Hindfoot Relative to Shank (Calcaneal) Eversion (-) Value at Midstance; Forefoot Relative to Hindfoot Abduction: Forefoot Relative to Hindfoot Abduction (-) at Midstance.

Table 3: Bivariate correlation matrix for predictor variables and for the foot with the greater foot progression angle (High FPA).

	Foot Progression Angle (deg)	Total hip rotation ROM (deg)	Ankle dorsiflexion ROM (deg)	RCSP (deg)	Thigh relative to lab rotation (deg)	Shank relative to lab rotation (deg)	Hindfoot relative to Shank Eversion (deg)
Total hip rotation ROM	0.28*						
Ankle dorsiflexion ROM	0.27*	0.49**					
RCSP	-0.25	-0.01	-0.02				
Thigh relative to lab rotation	0.46**	0.27	0.10	0.09			
Shank relative to lab rotation	0.60**	0.17	0.07	0.12	0.86**		
Hindfoot relative to Shank eversion	-0.34*	0.03	-0.43	-0.32*	-0.30*	-0.37*	
Forefoot relative to Hindfoot abduction	-0.12	0.13	-0.06	-0.29	-0.18	-0.34*	-0.36

Abbreviations: Foot Progression Angle: Foot Progression Angle on the High FPA Foot at Midstance, (-) =toe-out angle; Total Hip Rotation ROM: the Sum of Goniometric Measurement of Hip Internal and External Rotation Range of Motion in Pronelying; Ankle Dorsiflexion ROM: Goniometric Measurement of Ankle Dorsiflexion Range of Motion in Pronelying; Resting calcaneal stance position (RCSP): Goniometric Measure of Frontal Planecal Canoeal Position Relative to the Floor Assessed in Standing; Thigh relative to lab rotation: Thigh Segment Relative Tolabexternal Rotation (-) Value at Midstance; Shank Relative Tolabrotation: Shank Segment Relative Tolabexternal (-) Rotation Value at Midstance; Hindfoot Relative to Shank eversion: Hindfoot Relative to Shank (Calcaneal) Eversion(-) Value at Midstance. Forefoot Relative to Hind Foot abduction: Forefoot Relative to Hindfoot Abduction (-) at midstance.*Significance level (1-tailed), P<0.05; **: P<0.01

motion graph of High FPA is illustrated in Figure 1. There were no group differences in walking speed or in the dynamic (gait kinematic) variables.

Correlation and regression analyses:

Static (goniometric) model: The Pearson product moment

correlation coefficients for the static predictor variables in this model are shown in (Table 3). Total hip rotation (r=0.29), ankle dorsiflexion range of motion (r=0.32), and resting calcaneal stance position (RCSP; r=0.25) were significantly correlated with FPA. The multiple regression analysis for static predictor variables is shown in Table (4). The static predictor and group

Table 4: Multiple regression analysis of static (goniometric) predictors of foot progression angle on the foot with the greater FPA(HighFPA).

	Step 1			Step 2			Step 3			Step 4		
	β	P	R ²	β	P	R ²	β	P	R ²	β	P	R ²
Total Hip Rot ROM	0.28	0.07		0.21	0.21		0.21	0.20		0.09	0.61	
Ankle dorsiflexion ROM				0.19	0.26		0.19	0.24		0.13	0.41	
RSCP							-0.25	0.10		-0.25	0.10	
d1										0.03	0.88	
d2										0.17	0.35	
d3										-0.27	0.18	
R ² change			0.08			0.03			0.06			0.11
Total R ² change			0.08			0.11			0.17			0.28

dummy variables accounted for 28% of total High FPA variance, which did not reach statistical significance. Based on these results, none of the static predictor variables had a strong contribution to FPA variance.

Dynamic (gait kinematic) model: Pearson product moment correlation coefficients for the dynamic predictor variables in this model are shown in Table (3). Thigh lateral rotation ($r=0.46$) and shank lateral rotation ($r=0.60$) relative to the laboratory were positively correlated with FPA. Thigh and shank rotation relative to the laboratory were highly correlated with each other ($r=0.86$). Hindfoot relative to shank eversion was also correlated with FPA ($r=-0.34$). The multiple regression analysis for dynamic predictor variables is shown in Table (5). Thigh lateral rotation and shank lateral rotation relative to the laboratory at midstance accounts for 37% of FPA variance ($P<0.01$). Thigh lateral rotation relative to the laboratory had a unique contribution of 21% to FPA variance, while shank lateral rotation relative to the laboratory uniquely contributed 16% of FPA variance ($P<0.01$). The addition of hindfoot relative to shank eversion, forefoot relative to hindfoot abduction, and group classification had a negligible contribution FPA variance that was not statistically significant. The time series motion graphs of thigh relative to lab and shank relative to lab rotation are illustrated in Figure (1).

DISCUSSION

Foot progression angle (FPA), or “toe-out angle” is associated with elevated plantar stresses and loads that often lead to skin injury in adults with DMPN. This investigation sought to identify lower extremity motion variables that contribute to FPA in this clinical population. Using a comprehensive and unique approach to the characterization of FPA in a cohort of non-diabetic and diabetic participants, some key findings have emerged. Surprisingly, static (goniometric) measures of total hip rotation and ankle dorsiflexion do not uniquely or collectively predict FPA in adults with or without DMPN despite group differences in total hip motion. However, lateral rotation of the thigh and shank segments relative to the laboratory predicted 37% of variance in self-selected FPA, irrespective of the presence of diabetes. Also, intrinsic foot motion and alignment did not strongly contribute to FPA. These results suggest that adults with and without DMPN have similar lower extremity motion profile that influences

foot position during gait. To the authors’ knowledge, this is the first investigation to examine specific FPA characteristics and contribution of static (goniometric) and dynamic (gait kinematic) factors to FPA variance in a population of adults with and without DMPN. Additionally, this study is the first to assess the influence of goniometric measurements of hip rotation to FPA across a spectrum of individuals with and without diabetes mellitus.

Static (goniometric) predictors: Static predictors of FPA in the current study were goniometric measures of alignment and mobility of select lower extremity joints. One of the purposes of this study was to identify impairment-based predictor variables that contribute to FPA at midstance in participants with and without DMPN and a prior history of ulceration. Cibulka et al. [9], reported that clinical measures of passive hip medial (internal) rotation and tibial torsion significantly explain FPA in a cohort of healthy adults. The current investigation expands on these findings using a modeling approach that includes clinical measures of foot and ankle function in a population of adults with diabetes. Static (goniometric) predictors did not contribute strongly to FPA variance despite limitations in hip rotation range of motion in the DMPN+NPU group. Differences in the study cohort (healthy young adults versus adults with DMPN) may explain the discrepancy in the relative contribution of clinically measured hip rotation to FPA between these studies. Though select clinical measures of foot and ankle mobility are associated with elevated regional peak plantar pressure in adults with DMPN [18,19], they do not significantly account for variance in FPA. This suggests that therapeutic interventions targeting ankle dorsiflexion and hip rotation range of motion for FPA modification as an offloading strategy may not appropriate in this population.

Dynamic predictors: Results from this study show that thigh and shank lateral rotation relative to the laboratory at midstance predicted 37% of the variance in FPA. In a similar study, Lee et al. [26], reported that relative hip and knee rotation measures were moderately correlated with FPA ($r=0.49$) in children with diplegic cerebral palsy, and that femoral anteversion and tibial torsion explained 25% of FPA variance. Moreover, Cochrane and colleagues reported that changes in the degree of thigh, shank, and foot lateral rotation were concomitants of an induced increase in external FPA of at least 10° in a cohort of

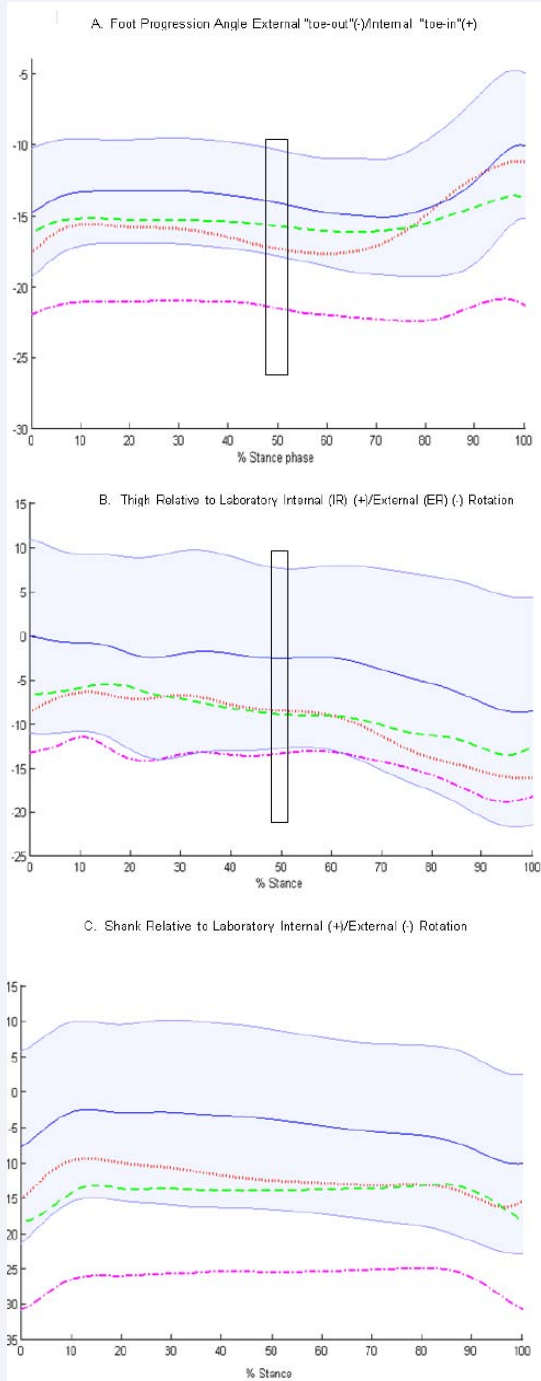


Figure 1 Time series motion graphs of dynamic predictor variables during the stance of walking. The blue line and shaded region represents the mean \pm 1 standard deviation of the motion for the CON group. Boxed regions represent values used in the analysis.

CON: Non-Diabetic Control Participants; DM: Diabetes Mellitus without Peripheral Neuropathy Group; DMPN-NPU: Diabetes Mellitus with peripheral Neuropathy without a Previous Neuropathic Plantar Ulcer; DMPN+NPU: Diabetes Mellitus with Peripheral Neuropathy with a previous Neuropathic Plantar Ulcer. Motion variables: A. Foot Progression Angle External "toe-out"/Internal "toe-in": Foot progression angle on the High FPA foot (-) =toe-out angle; B. Thigh segment relative to laboratory internal (IR) (+)/external (ER) (-); C. Shank segment relative to laboratory internal (IR) (+)/external (ER) (-) rotation

participants with and without knee osteoarthritis. It should be noted that the current study did not include measurement or analysis of other dynamic kinematic or structural variables that could influence FPA magnitude, which could explain the relative contributions of global rotations of the thigh and shank to foot position during gait. Collectively, findings from these studies support the assertion that a cluster of structural and alignment variables could influence FPA magnitude. Subsequently, models of FPA that include radiographic measures of tibial and femoral torsion, among others, in adults with DMPN may be more informative.

Changes in intrinsic foot morphology and function are clinically relevant with respect to plantar skin injury risk in adults with DMPN. The current investigation examined the contribution of intrinsic foot mobility and alignment to FPA using a multi-segment foot model. Dynamic measures of inter-segmental foot mobility, namely hindfoot relative to shank eversion and forefoot relative to hindfoot abduction, did not strongly predict FPA. The collinearity of shank lateral rotation and segmental foot variables potentially explains the negligible contribution of hindfoot relative to shank eversion and forefoot relative to hindfoot abduction to FPA variance. Further, the relationship between shank lateral rotation and hindfoot relative to shank eversion could be illustrative of the previously reported coupled motions of shank lateral rotation with hindfoot eversion during stance [43-45]. Results from this study indicate that movement impairments of the foot and ankle that are predictive of elevated regional plantar stresses may not influence FPA.

Treatment options for offloading areas of the foot susceptible to ulceration are often time intensive and cost prohibitive [46]. Rosenbaum reported significant reductions in medial plantar stresses with decreased FPA (in-toeing) compared with walking with increased FPA (out-toeing) in healthy individuals [12]. FPA modification as a gaiter training strategy could serve as a simple, cost effective therapeutic strategy that helps to minimize risk of elevated plantar stresses that often lead to NPU development in adults with DMPN. Static alignment measures of lower extremity function do not strongly reflect foot position during gait at midstance. Therefore, the dynamic kinematic contributors to foot position at midstance (e.g., thigh and shank) may serve as targets for verbal or tactile cueing to achieve optimal FPA for gait retraining tasks.

There are limitations associated with this study. A larger sample size may have allowed a more thorough exploration of the many alignment and position variables that might predict FPA magnitude. In addition, there may have been potential for lead in or lead out effects since we elected to truncate the walking distance. As noted above, this study did not include radiographic measures in the protocol primarily due to a lack of previous indication for their utility in predicting FPA. Given the reported relationship between calcaneal inclination angle, a radiographic alignment measure of the foot and ankle, and elevated regional plantar stresses in adults with DMPN [14], static alignment and bony abnormalities of the lower extremity may also be static predictors of FPA in adults with and without DMPN and a prior history of ulceration.

CONCLUSION

In adults with and without DMPN and a prior history of ulceration, dynamic variables are significant contributors to FPA variance. Lateral rotation of the proximal segments (thigh and shank) at the midstance phase of gait explained 37% of the variance in FPA. These findings suggest that targeting the thigh and shank for verbal or tactile cueing may be a potential strategy when trying to alter walking movement patterns towards decreasing external (lateral) FPA to minimize risk of elevated regional plantar stresses in adults with DMPN at risk for ulceration.

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