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Radiographic-directed local coordinate systems critical in kinematic analysis of walking in diabetes-related medial column foot deformity

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Abstract

Diabetic foot deformity onset and progression maybe associated with abnormal foot and ankle motion. The modified Oxford multi-segmental foot model allows kinematic assessment of inter-segmental foot motion. However, there are insufficient anatomical landmarks to accurately representation the alignment of the hindfoot and forefoot segments during model construction. This is most notable for the sagittal plane which is referenced parallel to the floor, allowing comparison of inter-segmental excursion but not capturing important sagittal hind-to-forefoot deformity associated with diabetic foot disease and can potentially underestimate true kinematic differences. The purpose of the study was to compare walking kinematics using local coordinate systems derived from the modified Oxford model and the radiographic directed model which incorporated individual calcaneal and 1st metatarsal declination pitch angles for the hindfoot and forefoot. We studied twelve participants in each of the following groups: (1) diabetes mellitus, peripheral neuropathy and medial column foot deformity (DMPN+), (2) DMPN without medial column deformity (DMPN–) and (3) age- and weight-match controls. The modified Oxford model coordinate system did not identify differences between groups in the initial, peak, final, or excursion hindfoot relative to shank or forefoot relative to hindfoot dorsiflexion/plantarflexion during walking. The radiographic coordinate system identified the DMPN+ group to have an initial, peak and final position of the forefoot relative to hindfoot that was more dorsiflexed (lower arch phenotype) than the DMPN– group ($p < .05$). Use of radiographic alignment in kinematic

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Conflict of interest statement

The authors of this manuscript have no financial conflicts of interest relative to any content included in this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gaitpost.2014.03.010>.

modeling of those with foot deformity reveals segmental motion occurring upon alignment indicative of a lower arch.

Keywords

Multi-segmental; Foot; Model; Diabetes; Deformity

1. Introduction

Early kinematic gait analysis of the foot and ankle modeled the entire foot as a single segment [1,2]. Improvements in motion capture and processing technology has allowed the foot to be modeled as multiple segments [3–5], allowing previously missed movement impairments occurring at the hindfoot, midfoot, forefoot, and toes to be measured [6–8]. Multi-segmental models rely on palpation of bony landmarks assumed to be in reasonably standard location with one another [3]. In addition, because there are no obvious or accessible bony landmarks to define the orientation, hindfoot and forefoot models often align the zero location of the local coordinate system in the sagittal plane, parallel to the ground in the standing position [3,8]. Normalization of the hindfoot and forefoot allows comparison of excursion of motion but does not allow any comparisons of segmental alignment or position. This is not a significant limitation when the comparison of motion is between individuals or groups that have similar bony and foot alignment.

However, assumptions associated with this type of multi-segmental foot model may not be valid and may limit interpretation of kinematic data when the intent is to compare motion between groups with defined and measured differences in sagittal plane bony alignment, destruction of bony landmarks, or displacement of palpable bony prominences. Diabetic foot disease can include progressive foot deformity and bony destruction [9,10]. Accurate palpation of abnormal or displaced hindfoot and forefoot landmarks that are used to define alignment can be challenging (Fig. 1). Yet we speculate that kinematic analysis of walking and other weightbearing activities may identify key movement compensations that are early indicators of foot deformity onset and contributes to deformity progression when repeated with every step throughout the day.

Differences in individual foot bony alignment, measured from radiographs, have been incorporated into multi-segmental foot models. The Milwaukee [11] and Shriners Hospitals for Children Greenville foot models [12,13] offset the hindfoot and forefoot using calcaneal and 1st metatarsal declination pitch angles. These models have been used in the gait examinations of a number of adult and pediatric foot conditions (e.g. posterior tibialis tendon dysfunction [14], clubfoot [15], hallux rigidus [11], cerebral palsy [16], planovalgus [13]). Sagittal plane alignment measures of calcaneal pitch and 1st metatarsal declination angle can be reliably and easily measured from standard weightbearing radiographs, even in those with diabetic foot deformity [17].

Applying an individualized, local coordinate system alignment for the hindfoot and forefoot based on radiographic alignment can provide critical information for understanding the impact of deformity on motion and provide key evidence needed for early identification and

prevention of foot deformity. However, radiographic-directed coordinate systems for the hindfoot and forefoot have not been implemented in gait evaluations of adults with diabetes and foot deformity. The purpose of the study was to compare walking kinematics using a modified Oxford foot model and a radiographic-directed local coordinate system for the hindfoot and forefoot in individuals with and without diabetes and foot deformity.

2. Materials

2.1. Participants

A total of 36 subjects were recruited and signed the consent form, approved by our Institutional Review Board, prior to participation in this cross sectional study (Table 1). Twelve participants had diabetes mellitus, peripheral neuropathy, and medial column deformity (DMPN+, age = 59 (13) yrs), twelve had diabetes mellitus, peripheral neuropathy, without medial column deformity (DMPN–, age = 58 (8) yrs), and twelve were controls without diabetes mellitus, peripheral neuropathy, or medial column deformity (age = 57 (14) yrs).

2.2. Participant inclusion/exclusion criteria

Participants were considered for inclusion in the DMPN+ group if they met the following criteria: (1) Type 1 or Type 2 DM, (2) peripheral neuropathy defined as the inability to feel 5.07 Semmes–Weinstein monofilament on at least one location on the plantar surface of their foot [18,19], and (3) medial column deformity defined as meeting 2 of the following weightbearing clinical measures of foot alignment: (a) eversion of the calcaneus on the leg 5° [20], (b) medial longitudinal arch angle $<130^\circ$ (angle between the medial malleolus, inferior navicular tuberosity, and 1st metatarsal head) [20], (c) navicular height ≥ 24 mm (height from the ground to the inferior surface of the navicular [20,21], (d) arch index less than 0.263 [22] (dorsal foot height/truncated foot length) and e) peak plantar pressure on medial side of the midfoot > 290 kPa [23]. The DMPN– group met the criteria for DM and peripheral neuropathy and did not meet criteria for medial column deformity. The control group was age- and weight-matched. Subjects were excluded if they had current plantar ulcers, were unable to complete the study testing requirements, had lower extremity amputations greater than digits, or weighed more than 180 kg and had metal implants/pace makers (required for an imaging component of the study). The involved foot for the DMPN– and control groups was chosen based on the DMPN+ participant to whom they were matched.

3. Methods

3.1. Foot radiographs

Weightbearing lateral radiographs were taken of the involved foot of all study participants. Measurements were completed using iSite[®] Picture Archiving and Communication Systems (PACS) software (Philips Healthcare Informatics, Foster City, CA). Two measures were taken: (1) Calcaneal pitch-the angle between the line from the calcaneal tuberosity to the most plantar aspect of the distal calcaneus and the floor and (2) 1st metatarsal declination –

the angle between the line through the longitudinal axis of the 1st metatarsal and the floor [17].

3.2. Walking kinematic data collection

Walking kinematic data of the shank, hindfoot, and forefoot were captured with an 8-camera 200 Hz Vicon motion analysis system (Vicon MX, Los Angeles, CA, USA). Marker placement followed a modified Oxford foot model and has been previously described [3,8]. In short, ten millimeter diameter reflective markers for the shank were located on the fibular head, tibial tuberosity, medial and lateral malleoli, and a plate with four markers at the distal-lateral shank. Hindfoot markers were located at the sustentaculum tali, peroneal trochlea, and a plate with two markers was aligned with the bisection of the posterior calcaneus. Forefoot markers were placed on the head and base of the 1st and 5th metatarsals and a marker was placed between the 2nd and 3rd metatarsal heads. The multi-segmented foot model was built in Visual3D software (C-Motion Inc., Germantown, MD, USA). The orientation of the local coordinate system for the hindfoot and forefoot was built in two different manners. The modified Oxford method defined the hindfoot and forefoot sagittal plane axes such that the zero position was parallel to the floor during the standing calibration trial [3,8]. The radiographic-directed model is described in detail in the supplementary materials. Briefly, all three axes for the hindfoot and forefoot were initially oriented as previously described for the modified Oxford foot model. Individual calcaneal pitch and 1st metatarsal declination angles, obtained from weightbearing radiographs, were used to offset the anterior/posterior axis for both the hindfoot and forefoot.

Participants walked barefoot at their self-selected speed. Visual 3D software was used to calculate walking speed for the stride in which the variables of interest were measured. Five trials were analyzed for each individual.

3.3. Statistical analyses

A one-way analysis of variance was used to compare subject characteristics between groups for continuous variables (age, height, and weight) and Chi-square for discrete variables (sex, race). A one-way analysis of covariance was also used to compare walking kinematic and kinetic variables with stride speed as a covariate and a Bonferroni correction was applied to correct for multiple comparisons. The homogeneity of regression assumption was met as indicated by a nonsignificant group $\times$ walking speed interaction, $p > .10$ for all dependent variables. SPSS Statistics version 19 was used for all statistical analyses (SPSS Statistics Inc., Chicago, USA). A p value of .05 was considered statistically significant for all comparisons.

4. Results

4.1. Radiographic alignment measures

The DMPN+ group had a lower calcaneal pitch compared to the DMPN– and control groups ($p < .05$). First metatarsal declination was also less in the DMPN+ group compared to DMPN– group ($p < .05$) (Table 1).

4.2. Stride speed and plantarflexor power

Stride speed was slowest in the DMPN+ group compared to DMPN– and Control groups ($p < .05$). Peak ankle power was least in the DMPN+ group compared to DMPN– and control groups ($p < .01$). However, when differences in stride speed were statistically controlled, ankle power was no longer different between groups (Table 2).

4.3. Walking kinematics using the modified Oxford coordinate system

Prior to controlling for differences in stride speed between groups, the hindfoot relative to shank position at the end of stance was significantly less plantarflexed in the DMPN+ group compared to controls ($p < .05$). When group differences in stride speed were controlled, the modified Oxford coordinate system did not identify significant differences between groups in initial, peak, final, or excursion of hindfoot relative to shank or forefoot relative to hindfoot dorsiflexion/plantarflexion during walking (Table 2 and Fig. 2).

4.4. Walking kinematics using radiographic coordinate system

Hindfoot relative to shank dorsiflexion/plantarflexion was not significantly different between groups at the initial, peak, or final instances during the stance phase of gait (Table 2 and Fig. 2).

The DMPN+ group began stance in a forefoot relative to hindfoot position that was less plantarflexed (lower arch, $-28 \pm 6^\circ$) compared to the DMPN– group ($-41 \pm 6^\circ$, $p < .05$). The lower arch position continued throughout stance in the DMPN+ group as indicated by the less plantarflexed position of the forefoot relative to hindfoot measured at peak and at the end of stance ($p < .05$). The forefoot relative to hindfoot position was also significantly lower in the DMPN+ compared to controls at the final instance of stance (-37 ± 9 , -30 ± 9 , and -42 ± 9 , $p < .05$, respectively) prior to controlling for group differences in stride speed (Table 2 and Fig. 2).

5. Discussion

This study provides evidence that a multi-segmental foot model with a radiographic-directed local coordinate system is critical in the kinematic study of individuals with foot deformity. The modified Oxford coordinate system is a solution to difficulty in palpating key bony landmarks, essentially normalizing the starting position of the hindfoot and forefoot segments to the ground in standing and allowing comparison of excursion between segments during walking. The addition of a radiographic-directed local coordinate system provides a more anatomically accurate examination of the impact of medial column deformity on sagittal plane kinematics.

The modified Oxford coordinate system demonstrated that those with and without diabetes and medial column foot deformity move their hindfoot relative to shank and forefoot relative to hindfoot through a similar excursion and pattern during the stance phase of gait. Turner et al. [6], using the same modified Oxford multi-segmental foot model used in this study, also report no difference in hindfoot relative to shank excursion between those with and without diabetes and foot complications. However, Deschamp et al. [24] and Rao et al. [25], using

slightly different foot models, report a reduction in hindfoot relative to shank excursion during walking in those with DMPN compared to healthy controls. Past work using single segment foot models have been similarly inconsistent when examining motion between the foot segment and the shank [26–30]. The source of the inconsistency across studies is not readily apparent. However, it is our hypothesis that kinematic analysis of walking, particularly at slow walking speeds (around 1 m/s), may not be a task that is consistently sensitive to changes associated with chronic diabetes. Total sagittal plane excursion of the foot segment relative to the shank across studies is surprisingly similar, most within a range of 15° to 20° [6,24,28], and group differences range from 2° to 7° [6,24,25]. Future study would benefit from inclusion of kinematic analysis of tasks that are more challenging and clearly and consistently measure deficits associated with complications from chronic diabetes. Such task might include heel rise, stair ascent/descent, and inclusion of a higher velocity walking task [8].

The modification of the local coordinate system of the hindfoot and forefoot segments in the sagittal plane, to reflect radiographic alignment of the calcaneus and 1st metatarsal provided critical information in the study of diabetes-related foot deformity. Although the modified Oxford coordinate system identified similar joint excursions and patterns, the addition of the radiographic local coordinate system allowed us to incorporate abnormalities in starting alignment and begin to study the implications of motion about segments that are no longer optimally aligned. Data from this study provided evidence that hindfoot relative to shank motion occurs in a relatively more plantarflexed position of the segments and the forefoot relative to hindfoot motion occurs in a more dorsiflexed or low arch position. We hypothesize that these joint alignment abnormalities result in a new load bearing surface that may not be suited or capable of force and motion transmission [31], posing a greater risk for progressive deformity, a significant challenge in individuals with diabetes [32].

There are limitations associated with the radiographic local coordinate system. The most important is to understand the assumptions of this particular foot model and avoid conclusions about joint alignment. The hindfoot segment assumes rigidity of the talocalcaneal joint. This assumption is supported by work by Hamel et al. [31], in a cadaver gait simulation study, which found only a small amount of independent motion of the calcaneus on the talus (5° dorsiflexion and 7° of internal rotation) and only during initial loading in the anatomically intact specimen. However, the validity and impact of this assumption should be examined as talocalcaneal joint deformity progresses. Additionally, the current model excludes the midfoot and models the forefoot as a rigid body including the 1st through 5th metatarsals.

The radiographic local coordinate system model also only incorporated sagittal alignment measures. Motion in the foot is a complex coupling of motion across all three cardinal planes of movement [33]. Plain radiographs, taken in a static standing alignment applied to a segment that is being dynamically loaded during walking is an oversimplification. Angular measures taken from sagittal radiographs are subject to errors associated with the foot structure being out of plane or oblique to the plane of the camera. In our experience the hindfoot was generally well aligned with the plane of the radiograph, however the forefoot in our DMPN with deformity group was 8° more abducted relative to the hindfoot and could

have resulted in errors in the 1st metatarsal declination angle. Finally, the radiographic local coordinate system fails to incorporate transverse and frontal plane alignment as well as information about joint mobility and altered axes of motion that will impact how and when the foot moves. Improvements in model complexity, motion capture capabilities, and integration of dynamic imaging techniques will certainly result in new and important discoveries in the future.

6. Conclusion

This study demonstrates that those with diabetes mellitus, peripheral neuropathy, and medial column foot deformity do not differ in total excursion of hindfoot relative to the shank or forefoot relative to the hindfoot during walking. However, use of radiographic alignment in kinematic modeling of those with foot deformity reveals segmental alignment indicative of a lower arch. Motion imposed upon abnormal segmental alignment could place the foot at greater risk of injury and progressive deformity.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Radiograph of a control participant (1) and two participants with diabetes mellitus, peripheral neuropathy, and deformity demonstrating the spectrum of deformity as well as the destruction and displacement of bony landmark in severe deformity (2 and 3). (a) 1st metatarsal to floor angle and (b) calcaneal pitch to floor angle.

Walking

Fig. 2.

Walking stance phase kinematics summarized for the modified Oxford coordinate system (left column) and the radiograph coordinate system (right column) for (A) hindfoot on shank dorsiflexion/plantarflexion and (B) forefoot on hindfoot dorsiflexion/plantarflexion. Shaded band represents the mean $\pm$ 1 standard deviation for the control group. Solid line is the mean $\pm$ 1 standard deviation bars for the group with diabetes, peripheral neuropathy and deformity, and the dotted line and bars is the mean $\pm$ standard deviation for the group with diabetes, peripheral neuropathy, without deformity (* $p < .05$). Note the ability of the radiographic coordinate system model to identify the more dorsiflexed position of the forefoot relative to the hindfoot throughout the stance phase of gait.

Table 1

Participant demographics and measures of foot alignment.

	DMPN+ (n = 12)	DMPN- (n = 12)	Controls (n = 12)
Age (yr) *	59 (13)	58 (8)	57 (14)
Sex (male/female)	7/5	8/4	8/4
Height (m) *	1.70 (0.08)	1.76 (0.09)	1.74 (0.11)
Weight (kg) *	110 (24)	113 (28)	108 (30)
BMI (kg/m ²) *	38 (9)	36 (9)	35 (8)
Type of DM (1/2)	1/11	2/10	
Duration of DM *	17 (11)	18 (10)	
HbA1c *	8.1 ^a (2.6)	7.5 (2.9)	5.2 (1.7)
Biothesiometry *	40 ^d (14)	39 ^e (15)	20 (14)
Race (Caucasian/African American)	8/4	9/3	8/4
Involved side (right/left)	6/6	6/6	7/5
Participants with ulcer history involved side	6	3	0
Clinical measures of alignment			
Navicular height (mm) involved *	24 ^{b,d} (5)	37 (8)	38 (5)
Calcaneal eversion (°) *	6 (6)	3 (4)	4 (4)
Medial longitudinal arch angle *	122 ^{b,d} (7)	150 (12)	145 (8)
Arch index *	0.288 ^c (0.055)	0.342 (0.067)	0.344 (0.031)
Medial midfoot peak plantar pressure (N/cm ²) *	27 ^{a,c} (28)	8 (8)	7 (7)
Radiographic measures of alignment			
Calcaneal pitch *	11 ^{b,c} (5)	18 (5)	16 (6)
1st metatarsal declination *	19 ^a (3)	22 (2)	20 (3)

Abbreviations: DMPN+, diabetes mellitus, peripheral neuropathy, and medial column deformity; DMPN-, diabetes mellitus, peripheral neuropathy, without medial column deformity.

^aDMPN+ is different than DMPN- ($p<.05$).

^bDMPN+ is different than DMPN- ($p<.01$).

^cDMPN+ is different than Controls ($p<.05$).

^dDMPN+ is different than Controls ($p<.01$).

^eDMPN- is different than Controls ($p<.01$).

* Values are given as the mean (standard deviation) or number.

Table 2

Walking kinematic.

	DMPN+ (n = 12)	DMPN- (n = 12)	Control (n = 12)
Walking: stance phase kinematics and kinetics			
Stride speed (m/s)	0.7 ^a (0.3)	1.0 ^b (0.3)	1.2 (0.2)
Peak ankle power (W/kg)	1.3 (1.0)	2.3 (1.1)	3.1 (0.7)
Traditional coordinate system			
Initial hindfoot relative to shank	3	1	1
Plantarflexion (-)/dorsiflexion (+) (°)	(5)	(5)	(4)
Initial forefoot relative to hindfoot	0	-1	0
Dorsiflexion (+)/plantarflexion (-) (°)	(3)	(4)	(4)
Peak hindfoot relative to shank	13	13	12
Dorsiflexion (+) (°)	(3)	(4)	(4)
Peak hindfoot relative to shank	-5	-6	-8
Plantarflexion (-) (°)	(5)	(7)	(5)
Peak forefoot relative to hindfoot	7	7	7
Dorsiflexion (+) (°)	(3)	(4)	(2)
Peak forefoot relative to hindfoot	-4	-5	-6
Plantarflexion (-) (°)	(3)	(5)	(5)
Final hindfoot relative to shank	1	-2	-6
Plantarflexion (-)/dorsiflexion (+) (°)	(5)	(7)	(5)
Final forefoot relative to hindfoot	-3	-4	-6
Dorsiflexion (+)/plantarflexion (-) (°)	(4)	(6)	(5)
Total hindfoot relative to shank sagittal	18	19	20
Plane excursion	(3)	(5)	(5)
Total forefoot relative to hindfoot	11	13	13
Sagittal plane excursion	(4)	(4)	(4)
Radiographic coordinate system			
Initial hindfoot relative to shank	14	19	16
Plantarflexion (-)/dorsiflexion (+) (°)	(6)	(8)	(8)
Initial forefoot relative to hindfoot	-28 ^c	-41	-37
Dorsiflexion (+)/plantarflexion (-) (°)	(6)	(11)	(9)
Peak hindfoot relative to shank	24	31	27
Dorsiflexion (+) (°)	(6)	(8)	(9)
Peak forefoot relative to hindfoot	-22 ^c	-33	-30
Dorsiflexion (+)/plantarflexion (-) (°)	(6)	(10)	(9)
Final hindfoot relative to shank	12	17	9
Plantarflexion (-)/dorsiflexion (+) (°)	(7)	(8)	(9)

	DMPN+	DMPN–	Control
	(n = 12)	(n = 12)	(n = 12)
Final forefoot relative to hindfoot	–30 ^c	–44	–42
Dorsiflexion (+)/plantarflexion (–) (°)	(7)	(12)	(9)

Statistical comparisons of kinetic and kinematic variables were completed with stride speed as the covariate. Values reported in the table are the original (unadjusted for stride speed) mean (standard deviation).

Abbreviations DMPN+ diabetes mellitus; peripheral neuropathy; and medial column deformity; DMPN– diabetes mellitus; peripheral neuropathy; without medial column deformity.

^a DMPN+ is different than Controls ($p < .01$).

^b DMPN– is different than Controls ($p < .05$).

^c DMPN+ is different than DMPN– ($p < .05$).