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Adult-Acquired Flatfoot Deformity and Age-Related Differences in Foot and Ankle Kinematics During the Single-Limb Heel-Rise Test

During the 4 stages of adult-acquired flatfoot deformity (AAFD), care is mostly commonly sought by patients at stage 2, at which both symptoms and foot deformity begin to impair functional ability. Stage 1 AAFD is marked by pain and swelling along the posterior tibial tendon, without foot deformity.[4,6] Stage 2 AAFD is characterized by degeneration and elongation of the posterior tibial tendon, as well as flexible flatfoot deformity,[8,20,23] including damage to the midfoot joint capsules (eg, talonavicular and naviculocuneiform) and associated ligaments (eg, spring ligament).[7] Operative care is typically indicated at stage 3, when the flatfoot deformity becomes fixed, and at stage 4, when deformity progresses to the ankle joint.[6] Foot deformity associated with AAFD can result in decreased stability of the midfoot, which is needed for the efficient transfer of force from the rearfoot to the forefoot. Thus, stage 2 is a critical time for nonoperative interventions. At this stage, therapeutic interventions that lead to increased midfoot stability may result in improved midfoot function and less strain on the posterior tibialis tendon during daily tasks.

Clinical data suggest that individuals with AAFD exhibit impaired ability to perform a single-limb heel rise.[1,15,16] The single-limb heel rise requires joint angles and moments similar to those of walking.[10] During the terminal stance phase of walking, the foot supinates in preparation

STUDY DESIGN: Cross-sectional laboratory study.

OBJECTIVE: To compare single-limb heel-rise performance and foot-ankle kinematics between persons with stage 2 adult-acquired flatfoot deformity (AAFD) and healthy controls.

BACKGROUND: The inability to perform a single-limb heel rise is considered a positive functional diagnostic test for AAFD. However, which foot motions contribute to poor performance of this task are not known.

METHODS: Fifty individuals participated in this study, 20 with stage 2 AAFD (mean ± SD age, 57.6 ± 11.3 years), and 15 older participants (age, 56.8 ± 5.3 years) and 15 younger participants (age, 22.2 ± 2.4 years) without AAFD as control groups. Forefoot (sagittal plane) and rearfoot (sagittal and frontal planes) kinematics were collected using a 3-D motion analysis system. Heel-rise performance (heel height) and kinematics (joint angles, excursions) were evaluated. One-way and 2-way analyses of variance were used to examine differences in heel-rise performance and kinematics between groups.

RESULTS: Individuals with AAFD and older controls demonstrated lower heel-rise height than those in the younger control group (*P*<.001). Persons with AAFD demonstrated higher degrees of first metatarsal dorsiflexion (*P*<.001), lower ankle plantar flexion (*P*<.001), and higher subtalar eversion (*P* = .027) than those in the older control group. Persons with AAFD demonstrated lower ankle excursion (*P*<.001) and first metatarsal excursion (*P*<.001) than those in the older control group, but no difference in subtalar excursion (*P* = .771).

CONCLUSION: Persons with stage 2 AAFD did not achieve sufficient heel height during a single-leg heel rise. Both forefoot and rearfoot kinematics in the sagittal plane, as opposed to the frontal plane, contributed to the lower heel height in participants with stage 2 AAFD. Older controls demonstrated lower heel-rise height than younger controls, indicating that clinical expectations of heel-rise performance may need to be adjusted for age. *J Orthop Sports Phys Ther 2014;44(4):283-290. Epub 25 February 2014. doi:10.2519/jospt.2014.4939*

KEY WORDS: *foot-ankle kinematics, pes planus, walking*

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for push-off.[21] Supination creates a more rigid midfoot, allowing the foot to function as a lever to transmit plantar flexor force from the rearfoot to the metatarsal heads and propel the body forward.[21] In terminal stance, persons with stage 2 AAFD demonstrate signs of midfoot instability, as indicated by reduced forefoot plantar flexion (PF) compared to that of healthy controls.[21,24,30] Due to similar loading of the foot during walking,[10] reduced forefoot PF also may impair the ability of individuals with AAFD to perform a single-limb heel rise.

The single-limb heel rise is often used as a test of plantar flexor endurance by counting the maximum number of repetitions at a specified heel-rise height.[13,18,19] However, the heel-rise height that individuals with AAFD achieve has not been investigated. To date, foot and ankle kinematics in persons with stage 2 AAFD have only been evaluated during the bilateral heel-rise test.[11] A previous study by Houck and colleagues[11] found that individuals with unilateral AAFD achieved similar bilateral heel-rise height, as well as similar forefoot (first metatarsal relative to calcaneus) and rearfoot (calcaneus relative to tibia) PF excursions, to that of healthy controls. However, the heel-rise height in persons with AAFD was achieved with the forefoot in significant pronation.[10,11] Given the higher loads associated with a single-limb heel rise, it is unclear whether persons with AAFD would continue to generate sufficient forefoot and rearfoot motion from a pronated foot position to achieve a similar heel height relative to controls. Further, if individuals with AAFD are unable to achieve a specified heel-rise height, it is unknown whether abnormal forefoot or rearfoot motions contribute to a lower height.

Although impaired single-limb heel-rise performance is often associated with AAFD, age may also influence performance and foot-ankle kinematics. For example, it has been reported that older adults have a more pronated foot posture than younger adults.[27,29] In addition, older adults have less forefoot and ankle excursions than younger adults.[29] Finally, while there is controversy over what defines a normal number of heel rises in healthy young adults,[18,19] it is clear that the number of heel rises declines with age, suggesting that endurance is impaired.[13] In addition, it is not clear whether heel-rise height also declines with age. Because the peak incidence of AAFD occurs at 55 years,[6] age may contribute to the difficulty individuals with AAFD experience with a heel rise. Recognizing this issue, most studies that have evaluated foot-ankle kinematics in AAFD have used age-matched controls.[11,16,24,30] Therefore, comparing younger and older controls will clarify whether restoring foot-ankle kinematics to that of a young adult is a reasonable clinical goal for older persons with AAFD.

The purpose of this study was to compare heel-rise performance, as well as forefoot and rearfoot kinematics, between persons with stage 2 AAFD, older controls, and younger controls. The first hypothesis was that individuals with AAFD would demonstrate lower heel-rise height compared to older controls. The second hypothesis was that, when compared to older controls, individuals with AAFD would demonstrate (1) joint angles consistent with pronation (lower first metatarsal PF and higher ankle PF in the sagittal plane, and lower subtalar inversion in the frontal plane), and (2) lower sagittal plane and frontal plane excursions (lower first metatarsal and ankle excursions in the sagittal plane, and lower subtalar excursion in the frontal plane). The third hypothesis was that older controls and younger controls would exhibit similar differences in heel-rise performance and foot-ankle kinematics (joint angles and excursions).

TABLE 1 Subject Characteristics*

	Controls			
	Younger (n = 15)	Older (n = 15)	AAFD (n = 20)	*P* Value
Age, y	22 ± 2.4[†]	56 ± 5.3	57 ± 11.3	<.001[‡]
Female, %	80	73	70	.798[§]
Weight, kg	64 ± 9.7[†]	77 ± 17.1	83 ± 17.0	.003[‡]
Height, m	1 ± 0.1	1 ± 0.1	1 ± 0.1	.115[‡]
BMI, kg/m²	22 ± 2.3[†]	26 ± 4.4[‖]	30 ± 5.2	<.001[‡]
Arch height index	0.35 ± 0.03	0.33 ± 0.03[‖]	0.30 ± 0.03	<.001[‡]
FFI-R (range)				
Pain (17%-100%)	16.7 ± 0	16.7 ± 0[‖]	33.0 ± 14.8	.001[‡]
Stiffness (17%-100%)	16.7 ± 0	17.2 ± 1.9[‖]	33.8 ± 14.5	<.001[‡]
Difficulty (10%-100%)	9.8 ± 0	10.4 ± 1.0[‖]	37.7 ± 18.4	<.001[‡]
Activity (17%-100%)	16.7 ± 0	16.7 ± 0[‖]	33.2 ± 20.3	.012[‡]
Social (17%-100%)	16.7 ± 0	16.7 ± 0.5	29.9 ± 22.2	.078[‡]
Average (15%-100%)	15.3 ± 0	15.6 ± 0.6[‖]	33.4 ± 16.3	.001[‡]

Abbreviations: AAFD, adult-acquired flatfoot deformity; BMI, body mass index; FFI-R, revised Foot Function Index.
**Values are mean ± SD unless otherwise indicated.*
[†]Older controls different from younger controls based on pairwise comparisons.
[‡]Significance of between-group differences using a 1-way analysis of variance.
[§]Significance of chi-square test.
[‖]AAFD different from older controls based on pairwise comparisons.

METHODS

Participants

Twenty individuals with stage 2 AAFD and 30 individuals without AAFD volunteered to participate in this study. Individuals with AAFD were

included if they were diagnosed with stage 2 AAFD by an orthopaedic surgeon. A clinical diagnosis of stage 2 AAFD was defined using 2 criteria, one related to tendinopathy and the other to flatfoot deformity. Participants had to have at least 1 of the following signs and symptoms of tendinopathy along the posterior tibial tendon: (1) tenderness to palpation, (2) swelling, or (3) pain with the unilateral heel rise. In conjunction with tendinopathy, participants in the AAFD group also had to demonstrate at least 1 sign of flexible flatfoot deformity (deformity could be passively corrected in a non–weight-bearing position), including (1) excessive forefoot abduction, (2) midfoot collapse, or (3) rearfoot abduction during standing. Persons were excluded from the AAFD group if they could not perform a heel rise (were unable to lift the heel off the floor) or had other foot conditions (eg, plantar fasciitis, insensate feet) or a history of foot or ankle surgery.

Demographic, self-report, and clinical measures were tabulated to describe the sample characteristics (**TABLE 1**). The revised Foot Function Index, a valid and reliable self-report measure of foot function, was used to describe functional status.[2] The arch height index (AHI) was calculated for all participants to determine foot posture. Briefly, the AHI was calculated by dividing the height of the dorsum of the foot by the truncated foot length (defined as the length from first metatarsal joint line to the back of the heel). Butler and colleagues[3] reported a normal AHI (90% weight bearing) to be 0.34 ± 0.03. A lower AHI represents a lower dorsum height in proportion to the truncated foot length, indicating a flatter foot posture.

A control group of 15 older adults similar in age to the AAFD group (50 to 65 years of age) and a control group of 15 younger adults (18 to 30 years of age) were recruited to examine the potential effect of age on heel-rise kinematics in healthy adults (**TABLE 1**). Because AAFD is more common in women,[17,23,26] both control groups were recruited to provide a sample of 70% to 80% women (**TABLE 1**). Persons were excluded from the control groups if they had a lower extremity injury in the past 6 months, a history of foot or ankle surgery, or pain with a unilateral heel rise.

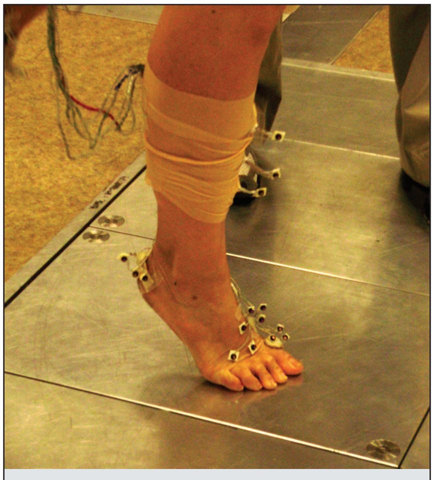

FIGURE 1. Foot and ankle kinematic model.

Given the sample size and a minimum power of 80%, the study was designed to detect differences between groups of variable magnitudes, depending on the analysis performed.[11] For peak heel-rise height normalized to truncated foot length, the sample size allowed for detection of a 10% difference between groups. For the comparison of AAFD versus older controls, we estimated the ability to detect differences of 6°, 4.5°, and 3° for first metatarsal PF/dorsiflexion (DF), ankle PF/DF, and subtalar inversion/eversion, respectively. For the comparison of younger versus older controls, we estimated the ability to detect differences of 3°, 3°, and 2° for first metatarsal PF/DF, ankle PF/DF, and subtalar inversion/eversion, respectively. All subjects were informed of the study procedures and signed a consent form approved by the University of Rochester Research Subjects Review Board and the Ithaca College All College Review Board for Human Subjects Research.

Kinematic Measurements

A 5-segment foot model, which included the hallux, first metatarsal, second to fourth metatarsals, calcaneus, and tibia, was used to collect kinematic data (**FIGURE 1**). First metatarsal kinematic variables were defined by first metatarsal motion relative to the calcaneus. Ankle and subtalar kinematic variables were defined by calcaneal motion relative to the tibia in the sagittal and frontal planes, respectively. Each segment was tracked by a set of 3 infrared markers on a thermoplastic molded platform, which was attached to the skin with double-sided adhesive tape. The error associated with skin-mounted markers in comparison to bone-mounted markers has been reported to be ±2.3° in the sagittal plane for the first metatarsal,[31] and ±2.6° and ±2.3° in the sagittal and frontal planes for the calcaneus, respectively.[22] Kinematic data were collected at a rate of 60 Hz from a 6-camera, 3-D motion-capture system (Optotrak; Northern Digital Inc, Waterloo, Ontario, Canada).

Force data were collected at a rate of 1000 Hz from a single force plate (model 9286; Kistler Group, Winterthur, Switzerland). Kinematic and force data were synchronized through MotionMonitor Version 7.24 software (Innovative Sports Training, Inc, Chicago, IL). Consistent with a previous study,[11] digitized points were used to establish an anatomic coordinate system for each segment, with the y-axis oriented superior/inferior (positive is superior), the x-axis oriented anterior/posterior (positive is anterior), and the z-axis oriented medial/lateral (positive is toward the subject's right). A digitized point at the base of the heel was used to estimate heel height during the heel-rise test. A fourth-order, zero-phase-lag, Butterworth filter with a cutoff frequency of 6 Hz was used to smooth kinematic data. A Cardan z-x-y sequence of rotations was used to calculate relative joint angles according to the standardization procedures suggested by Cole et al.[5]

Procedures

Participants were instructed to perform unilateral heel rises by lifting the heel as high as possible at a comfortable pace over a 5- to 15-second interval. To minimize discomfort and maximize peak heel height, participants stopped once they

TABLE 2 HEEL-RISE PERFORMANCE*

	Controls			
	Younger (n = 15)	Older (n = 15)	AAFD (n = 20)	*P* Value
Peak heel height, cm	11.8 ± 1.7†	10.6 ± 1.2‡	7.8 ± 1.3	<.001§
Truncated foot length, cm	18.3 ± 0.9	18.8 ± 1.9	18.7 ± 1.4	.560
Normalized peak heel height, %	63.4 ± 9.6†	55.8 ± 6.4‡	40.7 ± 8.1	<.001§

Abbreviation: AAFD, adult-acquired flatfoot deformity.
**Values are mean ± SD unless otherwise indicated.*
†Older controls different from younger controls based on pairwise comparisons.
‡AAFD different from older controls based on pairwise comparisons.
§Significance of between-group differences using a 1-way analysis of variance.

completed at least 3 repetitions (range, 3-8 repetitions). To assist with balance, participants were given fingertip-to-hand support. The difference in vertical ground reaction force between flatfoot stance and peak heel rise was assessed to determine if the AAFD group used more support. On average, the vertical ground reaction force in the AAFD group changed by a mean ± SD of 15.3% ± 11.4% body weight (range, 3.1%-35.1%), whereas the control group changed by 2.6% ± 1.8% body weight (range, 1.2%-8.9%). The greater change in vertical ground reaction force in the AAFD group suggests that these individuals used greater fingertip-to-hand support. However, the load on the foot for all groups during the single-limb heel rise was still substantially higher than that of a bilateral heel rise, which has been reported to range from 28% to 58% of body weight.[11]

Due to differences in foot posture between groups (see AHI values in **TABLE 1**), a common position between groups was needed to compare joint angles. The subtalar neutral position served as a common position for all subjects and was considered "0" for all joint-position kinematic variables. The examiner was an experienced physical therapist who was reliable in performing subtalar joint neutral positioning. The examiner's test-retest reliability in the AAFD group (n = 8) and control group (n = 15) was as follows: first metatarsal PF/DF, intraclass correlation coefficient [ICC] = 0.984 and standard error of measurement [SEM], 0.79°; ankle PF/DF, ICC = 0.933 and SEM, 1.2°; subtalar inversion/eversion, ICC = 0.963 and SEM, 0.59°. The error from the current study is similar to that of previously published studies (2 SEMs of 2.4° or less for all variables).[11,12] The examiner guided the subject from a relaxed standing posture to a subtalar neutral position by instructing the subject to raise or lower the arch of the foot until the medial and lateral sides of the talar head were equally prominent based on palpation. The subject maintained this position while 1 second of kinematic data were collected. Joint angles during the unilateral heel rise were reported in relation to the subtalar neutral position.

A similar first metatarsal PF angle in the subtalar neutral position was achieved between groups (younger, −26.8° ± 4.7°; older, −29.6° ± 5.4°; AAFD, −30.4° ± 8.6°; 1-way analysis of variance [ANOVA], *P* = .285).[11] Additionally, average ankle PF and subtalar inversion angles in the subtalar neutral position were similar between groups (1-way ANOVA pairwise comparisons, *P*>.05), indicating that the relative "0" position defined for each group was equivalent for all planned comparisons.

Data Analysis

To compare kinematic values between subjects, data were normalized to the heel-rise cycle (101 points). At least 3 heel-rise cycles, defined by ankle motion in the sagittal plane, were averaged for analysis. To eliminate the influence of different foot lengths on heel-rise performance, height was normalized to truncated foot length (**TABLE 2**). Truncated foot length was defined as the length from first metatarsal joint line to the back of the heel. Similar to a previous study,[11] 2 points of the heel rise were used for analysis: (1) the midpoint of the preparatory phase, defined by peak ankle DF, which occurred at approximately 15% of the heel-rise cycle; and (2) the peak of the rising phase corresponding to maximum ankle PF. The preparation phase represented the point in time when the foot was transitioning from one heel rise to the next. The peak heel rise was the point in time when the foot reached maximum height. Excursion was defined as the difference in joint angle between the preparation and rising phases. There were no significant kinematic differences between the left and right sides of control subjects, thus the left side was arbitrarily chosen for comparison.

Statistical Analysis

To test the first hypothesis related to heel-rise performance, a 1-way ANOVA was used to examine differences between groups. If the ANOVA was significant, pairwise comparisons were used to test which groups differed from each other. To test the effect of disease on performance, the AAFD group was compared to the older control group. To test the effect of age on performance, the older control group was compared to the younger control group. Pairwise comparison between AAFD and younger controls was not conducted due to the confounding effects of disease and age.

The second and third hypotheses regarding group differences in sagittal and frontal plane kinematic variables were assessed using (1) 2-way, mixed-effects ANOVAs (3 groups by 2 phases) for peak joint angles and (2) 1-way ANOVAs for joint excursions. This analysis was repeated for each kinematic variable of interest. For all ANOVAs, significant main

or interaction effects were followed by least-significant-difference procedures to determine significant pairwise comparisons (AAFD versus older controls and older controls versus younger controls).

To examine whether demographic variables (eg, gender and body mass index) should have been included as covariates in the ANOVAs, associations among demographic variables and foot-ankle kinematic variables were examined by group (Pearson correlation coefficients). There were no significant associations among demographic and kinematic variables for all 3 groups. All analyses were performed with SPSS Statistics Version 20.0 (IBM Corporation, Armonk, NY). Statistical significance was defined as a 2-tailed *P* value of .05 or less for all analyses.

TABLE 3 JOINT ANGLES BY GROUP DURING THE PREPARATION AND PEAK PHASES OF THE HEEL RISE*

Variable	Controls: Younger (n = 15)	Controls: Older (n = 15)	AAFD (n = 20)	*P* Value
Sagittal plane				
First metatarsal PF (−)/DF (+)				<.001†
Preparation, deg	6.7 ± 4.0	7.6 ± 5.9‡	14.1 ± 8.2	
Peak, deg	−19.2 ± 9.6	−11.7 ± 9.0‡	5.7 ± 11.3	
Ankle PF (−)/DF (+)				<.001†
Preparation, deg	10.5 ± 3.2	13.5 ± 4.8‡	9.0 ± 6.7	
Peak, deg	−22.1 ± 5.8§	−12.7 ± 6.7‡	−3.2 ± 8.0	
Frontal plane				
Subtalar Ev (−)/Inv (+)				.027‖
Preparation, deg	−5.8 ± 2.7	−5.6 ± 2.8‡	−8.1 ± 3.8	
Peak, deg	1.6 ± 3.4	1.1 ± 2.6‡	−0.8 ± 3.5	

Abbreviations: AAFD, adult-acquired flatfoot deformity; DF, dorsiflexion; Ev, eversion; Inv, inversion; PF, plantar flexion.
**Values are mean ± SD unless otherwise indicated.*
†Group-by-phase interaction.
‡AAFD different from older controls based on pairwise comparisons.
§Older controls different from younger controls based on pairwise comparisons.
‖Group main effect.

RESULTS

Normalized Heel-Rise Height

THE ANOVA COMPARING NORMALIZED heel-rise height between groups was significant (*P*<.001) (**TABLE 2**). Pairwise comparisons revealed that the AAFD group exhibited lower normalized heel height than older controls (*P*<.001). Also, the older control group demonstrated lower normalized heel height than the younger control group (*P* = .014).

Peak Joint Angles

There was a significant group-by-phase interaction for first metatarsal PF (*P*<.001) (**TABLE 3**). Pairwise comparisons showed that during the preparation-phase point (15% of heel-rise cycle), the AAFD group demonstrated higher first metatarsal DF compared to older controls (*P* = .005). At peak heel rise, the magnitude of the difference between groups increased, as the first metatarsal plantar flexed in older controls, whereas the first metatarsal in the AAFD group remained in a dorsiflexed position (pairwise comparisons, *P*<.001). The older and younger control groups demonstrated no significant differences in first metatarsal joint angle during either phase of the single-limb heel rise (pairwise comparisons, *P*>.05).

There was a significant group-by-phase interaction for ankle PF joint angle (*P*<.001) (**TABLE 3**). Pairwise comparisons showed that during the preparation phase, the AAFD group exhibited lower ankle DF than older controls (*P* = .016), and at peak heel rise the AAFD group demonstrated lower ankle PF than older controls (*P*<.001). Although there were no significant differences between the 2 control groups during the preparation phase, the older control group demonstrated lower ankle PF at peak heel rise compared to younger controls (*P* = .001).

There was a significant effect of group on subtalar inversion angle (*P* = .027) (**TABLE 3**). When averaged across phases, the AAFD group exhibited less inversion compared to older controls (*P* = .027). No differences in inversion were found between the 2 control groups.

Excursions

The ANOVAs comparing sagittal plane first metatarsal and ankle excursion between groups were significant (*P*<.001) (**TABLE 4**). Post hoc pairwise comparisons revealed that the AAFD group exhibited significantly lower first metatarsal (*P*<.001) and ankle (*P*<.001) excursions than older controls. Similarly, the older control group demonstrated significantly lower first metatarsal (*P* = .042) and ankle (*P* = .007) excursions than the younger control group. There were no differences in subtalar joint excursions between groups (**TABLE 4**).

DISCUSSION

THE NOVEL FINDINGS OF THIS STUDY are that heel-rise height and foot-ankle kinematics during the single-limb heel rise differed between individuals with stage 2 AAFD and older controls. These findings differ from a previous study that evaluated foot and ankle kinematics during a double-limb heel-rise test,[11] suggesting that the increased load of the single-leg heel rise can influence heel-rise height and foot-ankle kinematics. In the current study, individuals with AAFD exhibited lower single-limb heel height and lower fore-

foot and rearfoot excursions compared to the older control group. In agreement with previous studies evaluating foot kinematics,[11,21,24,28,30] the finding of lower first metatarsal PF underscores the role of midfoot instability in impaired heel-rise ability. The low ankle excursion was consistent with the premise that excessive rearfoot PF diminishes the ability of the ankle to contribute to a heel-rise height in persons with AAFD.[11] These kinematic findings emphasize the importance of developing clinical approaches to rectify abnormal kinematics of the forefoot and rearfoot. In addition, those in the older control group demonstrated lower heel height than those in the younger control group, suggesting that clinical expectations for older patients may need to be adjusted for age.

Previous studies have quantified the normal number of heel-rise repetitions for plantar flexor endurance,[13,18,19] yet a criterion to define a minimum heel-rise height has not been reported. This is important because heel-rise height may be indicative of the presence of AAFD. Consistent with previous studies,[15,16,28] participants with AAFD had difficulty performing the single-limb heel rise. Previous studies used the number of repetitions of a heel rise (more an endurance than a strength test) rather than heel-rise height to assess performance. The findings of the current study suggest that normalized heel height may be an additional metric during a single-leg heel rise to evaluate (1) calf strength and (2) foot function (see discussion below).

The altered forefoot and rearfoot joint angles in persons with AAFD were consistent with achieving a lower heel height. During the preparation phase of the heel-rise cycle, individuals with AAFD exhibited greater first metatarsal DF, lower ankle DF, and greater subtalar eversion than older controls (**TABLE 3**). These findings confirm that persons with AAFD transition between heel rises in a more pronated foot posture compared to older controls. On average, the AAFD group did not achieve first metatarsal PF at peak heel rise (5.7° first metatarsal DF) and achieved marginal ankle PF (mean, −3.2°). In contrast, the older controls achieved 11.7° of first metatarsal PF and 12.7° of ankle PF at peak heel rise. Parallel to the findings related to peak joint angles, reduced excursions also were observed in the AAFD group. The AAFD group displayed 37.1% less first metatarsal excursion and 42.4% less ankle excursion compared to older controls (**TABLE 4**).

TABLE 4 JOINT EXCURSIONS BY GROUP FROM PREPARATION PHASE TO PEAK HEEL RISE*

Variable	Controls: Younger (n = 15)	Controls: Older (n = 15)	AAFD (n = 20)	*P* Value
Sagittal plane				
First metatarsal excursion	25.8 ± 12.2†	19.4 ± 6.4‡	7.2 ± 6.6	<.001
Ankle excursion	32.6 ± 6.6†	26.2 ± 6.3‡	11.1 ± 6.3	<.001
Frontal plane				
Subtalar excursion	7.3 ± 3.4	6.8 ± 2.8	6.6 ± 3.1	.771

Abbreviation: AAFD, adult-acquired flatfoot deformity.
**Values are mean ± SD unless otherwise indicated.*
†Older controls different from younger controls based on pairwise comparisons.
‡AAFD different from older controls based on pairwise comparisons.

Consistent with clinical reports, persons with AAFD demonstrated subtalar eversion joint angles throughout heel-rise performance (**TABLE 3**). Because the subtalar inversion excursion was relatively small (approximately 7°), it is possible that differences in subtalar joint angles were not detected, given that skin-tracking errors have been estimated to be 2° to 3°.[22] Additionally, subtalar excursion was not significantly different between groups, reinforcing the lack of consistency in subtalar eversion as a sign of AAFD. Although two thirds of the subjects with AAFD failed to demonstrate subtalar inversion during the heel rise, one third of both the younger and older controls also failed to demonstrate subtalar inversion at peak heel rise (**FIGURE 2**). Taken together, the small magnitude and inconsistency of rearfoot eversion that characterized the AAFD group suggest that rearfoot eversion during a heel rise is of questionable clinical utility in assessing dynamic foot function in persons with AAFD.

Similar to a previous study using the bilateral heel-rise test,[11] the forefoot and rearfoot joint angles in the current study were biased toward foot pronation in persons with AAFD when compared to controls. However, evaluation of the single-limb heel rise led to more marked differences in heel-rise performance and kinematics. Houck and colleagues[11] reported that persons with AAFD demonstrated no differences in bilateral heel-rise height or foot and ankle excursions compared to controls. Yet, in the present study, there were marked differences among groups in heel height and sagittal plane excursions. For example, Houck et al[11] reported that approximately 50% of AAFD participants achieved some degree of first metatarsal PF during a bilateral heel rise. In contrast, only 30% of participants with AAFD achieved first metatarsal PF in the current study (**FIGURE 2**). The significance of this finding is highlighted by the fact that nearly all control subjects (younger and older) achieved first metatarsal PF. Thus, under a higher load, the forefoot and rearfoot did not attain sufficient excursion in persons with AAFD to achieve a heel-rise height comparable to controls.

The identification of abnormal kinematics consistent with AAFD may motivate strategies to stabilize the midfoot in participants with AAFD. For example, alterations in forefoot kinematics associated with AAFD may stimulate the

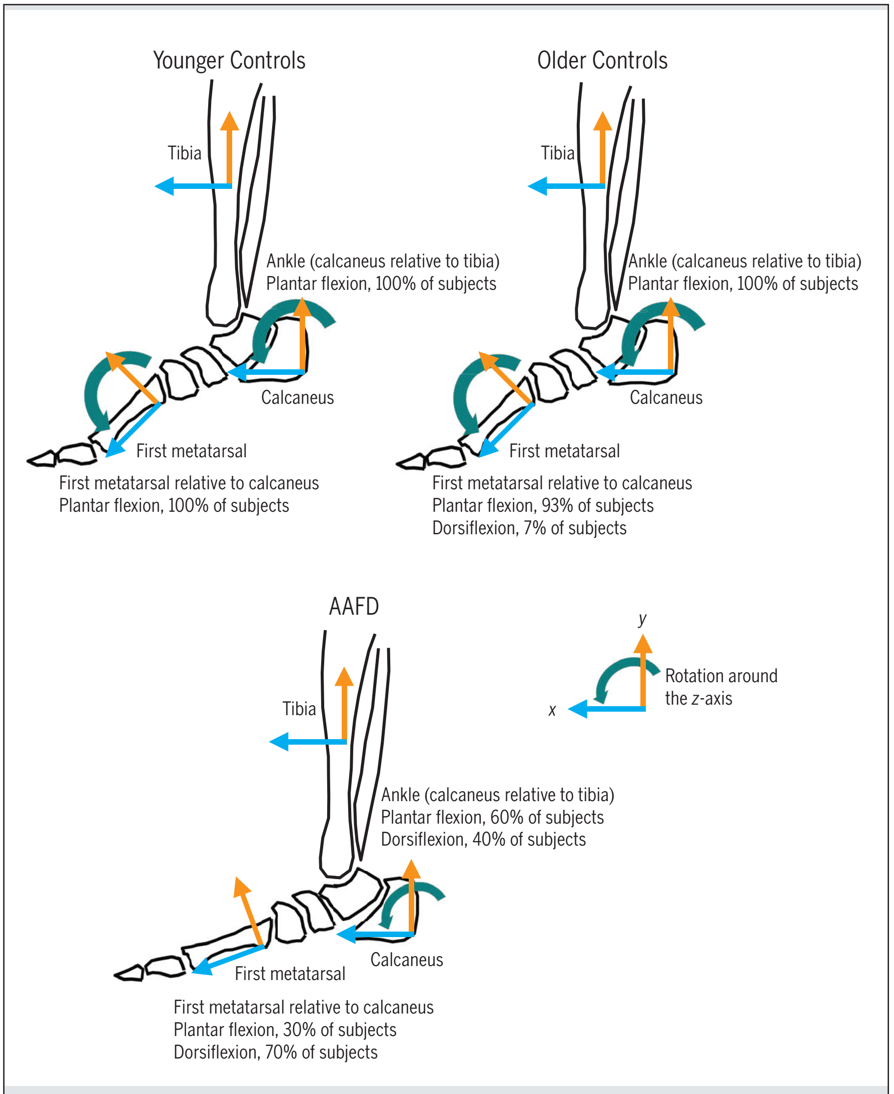

FIGURE 2. Percentage of people who achieved subtalar neutral position at the peak of the single-limb heel rise, by group. Abbreviation: AAFK, adult-acquired flatfoot deformity.

development of exercises that result in improved forefoot PF. Currently, studies evaluating exercises targeting the forefoot and its mechanics are limited.[9,14] In contrast, emphasis on rearfoot frontal plane control[1] or specific exercise for the posterior tibialis muscle[12,15] has been high. Similarly, orthotic strategies typically emphasize rearfoot control as opposed to forefoot control for patients with AAFD.[25] Yet, the findings of the current study, along with the study by Houck et al,[11] indicate that abnormal sagittal plane kinematics of both the forefoot and rearfoot need to be considered.

There were few kinematic differences between the older and younger control groups. The lower ankle PF in the older control group was the primary kinematic difference and likely contributed to the lower heel-rise height between these 2 groups. On average, the older control group exhibited 12% less peak heel-rise height than the younger control group (**TABLE 2**). Although these findings suggest an age-associated decline in heel-rise performance, a variety of factors in older adults may also influence peak heel height and ankle joint angles. For example, gender, weight, foot posture, foot and ankle mobility, and fitness level may modify expectations of heel-height performance and foot-ankle kinematics. The findings of the current study highlight the need for clinicians to expect slightly lower heel height during a single-limb heel rise in older participants.

Limitations

There are several limitations of the current study that should be considered when interpreting the results. The findings of the current study could have been influenced by the severity of AAFD, as determined by the inclusion criteria, and sample characteristics. For example, the groups differed significantly in terms of weight and body mass index (**TABLE 1**). However, it should be noted that weight was not associated with foot-ankle kinematics in the current study. The kinematic model used in our study lacked specificity with respect to foot joints and represented the sum of motion of several joints (ie, talonavicular, naviculocuneiform, medial cuneiform-first metatarsal). Also, a criticism of only reporting joint angles is that they are potentially influenced by the use of the subtalar neutral position to define a common foot position to compare foot-ankle kinematics. Therefore, both joint angles and excursions were reported. Further, the average subtalar neutral-position angle was statistically equivalent between groups, and the differences between groups were large, suggesting the comparisons in joint angles were not biased by the subtalar neutral position.

CONCLUSION

This study demonstrated that participants with stage 2 AAFD achieved lower heel-rise height during a single-leg heel rise compared to a healthy control group. Both forefoot and rearfoot kinematics in the sagittal plane, not the frontal plane, were altered in participants with stage 2 AAFD when compared to healthy controls. This finding suggests that abnormal kinematics of both the forefoot and rearfoot contribute

to the difficulty in achieving heel-rise height in persons with AAFD. In addition, the older control group demonstrated lower heel-rise height than the younger control group, indicating that clinical expectations of heel-rise performance may need to be adjusted for age. ◉

KEY POINTS

FINDINGS: Altered sagittal plane kinematics of the first metatarsal and ankle, as opposed to abnormal subtalar eversion, appear to be kinematic factors that contribute to a lower heel-rise height in persons with AAFD.

IMPLICATIONS: Heel-rise height during a single-limb heel rise may be a useful clinical metric in persons with AAFD. In contrast, assessing subtalar eversion during the single-limb heel rise may have limited clinical utility due to the small magnitude and inconsistency of this kinematic pattern in persons with AAFD.

CAUTION: While individuals with AAFD demonstrated abnormal foot and ankle kinematics, neither the cause of instability nor the mechanism to restore kinematics is known. Also, these findings are specific to the severity (stage 2) of AAFD and the kinematic methods used.

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REFERENCES

1. Alvarez RG, Marini A, Schmitt C, Saltzman CL. Stage I and II posterior tibial tendon dysfunction treated by a structured nonoperative management protocol: an orthosis and exercise program. *Foot Ankle Int*. 2006;27:2-8.
2. Budiman-Mak E, Conrad KJ, Mazza J, Stuck RM. A review of the foot function index and the foot function index – revised. *J Foot Ankle Res*. 2013;6:5. http://dx.doi.org/10.1186/1757-1146-6-5
3. Butler RJ, Hillstrom H, Song J, Richards CJ, Davis IS. Arch height index measurement system: establishment of reliability and normative values. *J Am Podiatr Med Assoc*. 2008;98:102-106.
4. Chhabra A, Soldatos T, Chalian M, et al. 3-Tesla magnetic resonance imaging evaluation of posterior tibial tendon dysfunction with relevance to clinical staging. *J Foot Ankle Surg*. 2011;50:320-328. http://dx.doi.org/10.1053/j.jfas.2011.02.004
5. Cole GK, Nigg BM, Ronsky JL, Yeadon MR. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *J Biomech Eng*. 1993;115:344-349.
6. Deland JT. Adult-acquired flatfoot deformity. *J Am Acad Orthop Surg*. 2008;16:399-406.
7. Deland JT, de Asla RJ, Sung IH, Ernberg LA, Potter HG. Posterior tibial tendon insufficiency: which ligaments are involved? *Foot Ankle Int*. 2005;26:427-435.
8. Gluck GS, Heckman DS, Parekh SG. Tendon disorders of the foot and ankle, part 3: the posterior tibial tendon. *Am J Sports Med*. 2010;38:2133-2144. http://dx.doi.org/10.1177/0363546509359492
9. Headlee DL, Leonard JL, Hart JM, Ingersoll CD, Hertel J. Fatigue of the plantar intrinsic foot muscles increases navicular drop. *J Electromyogr Kinesiol*. 2008;18:420-425. http://dx.doi.org/10.1016/j.jelekin.2006.11.004
10. Henriksen M, Aaboe J, Bliddal H, Langberg H. Biomechanical characteristics of the eccentric Achilles tendon exercise. *J Biomech*. 2009;42:2702-2707. http://dx.doi.org/10.1016/j.jbiomech.2009.08.009
11. Houck JR, Neville C, Tome J, Flemister AS. Foot kinematics during a bilateral heel rise test in participants with stage II posterior tibial tendon dysfunction. *J Orthop Sports Phys Ther*. 2009;39:593-603. http://dx.doi.org/10.2519/jospt.2009.3040
12. Houck JR, Tome JM, Nawoczenski DA. Subtalar neutral position as an offset for a kinematic model of the foot during walking. *Gait Posture*. 2008;28:29-37. http://dx.doi.org/10.1016/j.gaitpost.2007.09.008
13. Jan MH, Chai HM, Lin YF, et al. Effects of age and sex on the results of an ankle plantar-flexor manual muscle test. *Phys Ther*. 2005;85:1078-1084.
14. Jung DY, Kim MH, Koh EK, Kwon OY, Cynn HS, Lee WH. A comparison in the muscle activity of the abductor hallucis and the medial longitudinal arch angle during toe curl and short foot exercises. *Phys Ther Sport*. 2011;12:30-35. http://dx.doi.org/10.1016/j.ptsp.2010.08.001
15. Kulig K, Lederhaus ES, Reischl S, Arya S, Bashford G. Effect of eccentric exercise program for early tibialis posterior tendinopathy. *Foot Ankle Int*. 2009;30:877-885. http://dx.doi.org/10.3113/FAI.2009.0877
16. Kulig K, Popovich JM, Jr., Noceti-Dewit LM, Reischl SF, Kim D. Women with posterior tibial tendon dysfunction have diminished ankle and hip muscle performance. *J Orthop Sports Phys Ther*. 2011;41:687-694. http://dx.doi.org/10.2519/jospt.2011.3427
17. Kulig K, Reischl SF, Pomrantz AB, et al. Nonsurgical management of posterior tibial tendon dysfunction with orthoses and resistive exercise: a randomized controlled trial. *Phys Ther*. 2009;89:26-37. http://dx.doi.org/10.2522/ptj.20070242
18. Lunsford BR, Perry J. The standing heel-rise test for ankle plantar flexion: criterion for normal. *Phys Ther*. 1995;75:694-698.
19. Madeley LT, Munteanu SE, Bonanno DR. Endurance of the ankle joint plantar flexor muscles in athletes with medial tibial stress syndrome: a case-control study. *J Sci Med Sport*. 2007;10:356-362. http://dx.doi.org/10.1016/j.jsams.2006.12.115
20. Myerson MS. Adult acquired flatfoot deformity: treatment of dysfunction of the posterior tibial tendon. *J Bone Joint Surg Am*. 1996;78:780-792.
21. Ness ME, Long J, Marks R, Harris G. Foot and ankle kinematics in patients with posterior tibial tendon dysfunction. *Gait Posture*. 2008;27:331-339. http://dx.doi.org/10.1016/j.gaitpost.2007.04.014
22. Nester C, Jones RK, Liu A, et al. Foot kinematics during walking measured using bone and surface mounted markers. *J Biomech*. 2007;40:3412-3423. http://dx.doi.org/10.1016/j.jbiomech.2007.05.019
23. Neville C, Flemister A, Tome J, Houck J. Comparison of changes in posterior tibialis muscle length between subjects with posterior tibial tendon dysfunction and healthy controls during walking. *J Orthop Sports Phys Ther*. 2007;37:661-669. http://dx.doi.org/10.2519/jospt.2007.2539
24. Neville C, Flemister AS, Houck JR. Deep posterior compartment strength and foot kinematics in subjects with stage II posterior tibial tendon dysfunction. *Foot Ankle Int*. 2010;31:320-328. http://dx.doi.org/10.3113/FAI.2010.0320
25. Neville C, Houck J. Choosing among 3 ankle-foot orthoses for a patient with stage II posterior tibial tendon dysfunction. *J Orthop Sports Phys Ther*. 2009;39:816-824. http://dx.doi.org/10.2519/jospt.2009.3107
26. Parsons S, Naim S, Richards PJ, McBride D. Correction and prevention of deformity in type II tibialis posterior dysfunction. *Clin Orthop Relat Res*. 2010;468:1025-1032. http://dx.doi.org/10.1007/s11999-009-1122-1
27. Redmond AC, Crane YZ, Menz HB. Normative values for the Foot Posture Index. *J Foot Ankle Res*. 2008;1:6. http://dx.doi.org/10.1186/1757-1146-1-6
28. Ringleb SI, Kavros SJ, Kotajarvi BR, Hansen DK, Kitaoka HB, Kaufman KR. Changes in gait associated with acute stage II posterior tibial tendon dysfunction. *Gait Posture*. 2007;25:555-564. http://dx.doi.org/10.1016/j.gaitpost.2006.06.008
29. Scott G, Menz HB, Newcombe L. Age-related differences in foot structure and function. *Gait Posture*. 2007;26:68-75. http://dx.doi.org/10.1016/j.gaitpost.2006.07.009
30. Tome J, Nawoczenski DA, Flemister A, Houck J. Comparison of foot kinematics between subjects with posterior tibialis tendon dysfunction and healthy controls. *J Orthop Sports Phys Ther*. 2006;36:635-644. http://dx.doi.org/10.2519/jospt.2006.2293
31. Umberger BR, Nawoczenski DA, Baumhauer JF. Reliability and validity of first metatarsophalangeal joint orientation measured with an electromagnetic tracking device. *Clin Biomech (Bristol, Avon)*. 1999;14:74-76.

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1. M.C. Cöster, B.E. Rosengren, A. Bremander, M.K. Karlsson. 2015. Surgery for adult acquired flatfoot due to posterior tibial tendon dysfunction reduces pain, improves function and health related quality of life. *Foot and Ankle Surgery* **21**, 286-289. [CrossRef]
2. Mary K. Hastings, James Woodburn, Michael J. Mueller, Michael J Strube, Jeffrey E. Johnson, David R. Sinacore. 2014. Kinematics and kinetics of single-limb heel rise in diabetes related medial column foot deformity. *Clinical Biomechanics* **29**, 1016-1022. [CrossRef]