

Comparative Analysis of Human Gait While Wearing Thong-Style Flip-flops versus Sneakers

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Background: Flip-flops are becoming a common footwear option. Casual observation has indicated that individuals wear flip-flops beyond their structural limit and have a different gait while wearing flip-flops versus shoes. This alteration in gait may cause the anecdotal foot and lower-limb discomfort associated with wearing flip-flops.

Methods: To investigate the effect of sneakers versus thong-style flip-flops on gait kinematics and kinetics, 56 individuals (37 women and 19 men) were randomly assigned to a footwear order (flip-flops or sneakers first) and were asked to wear the assigned footwear on the day before and the day of testing. On each testing day, participants were videotaped as they walked at a self-selected pace across a force platform. A 2 (sex) $\times$ 2 (footwear) repeated-measures analysis of variance ($P = .05$) was used for statistical analysis.

Results: Significant interaction effects of footwear and sex were found for maximal anterior force, attack angle, and ankle angle during the swing phase. Footwear significantly affected stride length, ankle angle at the beginning of double support and during the swing phase, maximal braking impulse, and stance time. Flip-flops resulted in a shorter stride, a larger ankle angle at the beginning of double support and during the swing phase, a smaller braking impulse, and a shorter stance time compared with sneakers.

Conclusions: The effects of footwear on gait kinetics and kinematics is extensive, but there is limited research on the effect of thong-style flip-flops on gait. These results suggest that flip-flops have an effect on several kinetic and kinematic variables compared with sneakers. (J Am Podiatr Med Assoc 100(4): 251-257, 2010)

Flip-flops are becoming a common footwear option, and according to the NPD Group (Port Washington, New York), a provider of consumer and retail market research information, men's sports sandal sales in 2003 were up 5% from the previous year, whereas overall footwear sales were down 6%.¹ Also, the Surf Industry Manufacturers Association in 2007 reported that one of the top surf industry trends was sandal sales. The Surf Industry Manufacturers Association stated that overall footwear sales were down, but sandal sales were up more than \$300 million, which was an increase of \$50 million since 2004.² Although thong-style flip-flops are a type of sandal, the increase in sales of sandals noted by the Surf Industry Manufacturers Association does not necessarily mean an increase in the

thong style. However, it is interesting to note that men's thong-style flip-flop sales in department stores had a fourfold increase from 2002 to 2006 as reported by the NPD Group, which suggests that increased flip-flop sales contributed to the overall increase in sandal sales.³

Casual observation of individuals wearing flip-flops has indicated that people have a different gait while wearing flip-flops versus shoes. This observed altered gait may lead to compensation or unusual stresses that flip-flop wearers do not encounter while wearing a more traditional shoe such as an athletic sneaker. In fact, according to the American College of Foot and Ankle Surgeons in 2007,⁴ an increase in the use of flip-flops by teens and young adults has led to an increase in heel pain. American College of Foot and Ankle Surgeons spokesperson Marybeth Crane, DPM, FACFAS, stated, "We're seeing more heel pain than ever in patients 15 to 25 years old..."⁴ Furthermore, the American College of Foot and

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Ankle Surgeons recommends that patients with heel pain avoid flat shoes, owing to the paper-thin soles, and avoid walking barefoot because wearing flat shoes and walking barefoot provide little to no arch support.⁴ In fact, this recommendation received research support when a study by Carl and Barrett⁵ investigated the effects of flip-flops on plantar pressures and found that plantar pressures increase when wearing flip-flops compared with athletic shoes. This lack of arch support and cushioning in the heel of flip-flops could exacerbate any abnormalities in the biomechanics of foot motion and may perpetuate heel pain and inflammation. Plantar fasciitis has been found to be a source of heel pain and is responsible for 15% of all adult foot complaints. Furthermore, one major contributing factor to plantar fasciitis is wearing inappropriate footwear such as flip-flops. These statements suggest that flip-flops are a major cause of heel pain and should not to be worn if heel pain is present.⁴

Wearing flip-flops has also been linked to abnormal neuromuscular activity in athletes with iliotibial band friction syndrome, and wearing flip-flops less frequently is recommended by athletic trainers to reduce iliotibial band friction syndrome in athletes.⁶ Iliotibial band friction syndrome is caused by the iliotibial band rubbing over the prominence of the lateral femoral epicondyle from repetitive flexion and extension of the knee joint in activities such as running. This increased friction causes direct irritation of the iliotibial band or inflammation of the bursa under the epicondyle.⁷ In a case study,⁶ it was found that limiting the use of flip-flops as a casual footwear choice aided in the rehabilitation of a runner with iliotibial band friction syndrome. This suggests that flip-flops can contribute to pain in the lower extremity and that when pain is present, flip-flops are counterproductive to alleviating this pain.

Although the causal relationship between flip-flops and lower-extremity pain seems to be accepted clinically, the manner by which this is achieved is not; therefore, the purpose of this research project was to determine whether there is a difference in gait kinematics and kinetics when walking with flip-flops versus sneakers. Specifically, does wearing thong-style flip-flops alter stride length, ankle angle, knee angle, impulse, and two-dimensional (2-D) ground reaction forces? It was anticipated that the following would occur while walking in thong-style flip-flops compared with walking in sneakers: 1) a decrease in plantarflexion during the swing phase of the nonsupport leg, 2) an increase in the knee angle during the swing phase of the nonsupport leg, 3) a

decrease in the attack angle (the angle between anteroposterior force and vertical force) at heel contact, and 4) a decrease in stride length. The outcomes of this project should 1) provide a basis for how walking in thong-style flip-flops affects gait kinetics and kinematics compared with walking in sneakers and 2) provide insight into orthopedic problems, such as heel and foot pain, that may stem from the differences in gait associated with wearing flip-flops while walking.

Methods

Participants

Fifty-six college students (37 women and 19 men) participated in this project. The mean $\pm$ SD participant age was 20.85 ± 1.39 years; weight, 69.84 ± 14.36 kg; and height, 1.69 ± 0.13 m. Before participation, the participants completed a medical questionnaire to determine whether they had sustained a lower-extremity injury or had surgery in the past year and if they were aware of any other factor that may preclude them from successfully completing the requirements of this study. Approval for this study was obtained from the Institutional Review Board for the Protection of Human Subjects in Research at Auburn University.

Experimental Procedures

On reporting to the laboratory, participants were familiarized with the experimental protocol and provided informed consent before participation. Participants were assigned to a footwear order (either sneakers or thong-style flip-flops first) based on randomized participant number. Odd-numbered participants wore flip-flops first and even-numbered participants wore shoes first. Next, the participants were instructed to wear the corresponding footwear on the day before and the day of testing. The participants were then asked to wear the opposite footwear on the day before and the second day of testing. Participants wore their own personal flip-flops and sneakers. The criteria for participant footwear were that flip-flops must be thong style and sneakers must be athletic style. On both testing days, 25.4-mm surface retroreflective markers (B & L Engineering, Tustin, California) were placed on the right side of each participant at four anatomical locations: 1) the greater trochanter of the femur, 2) the lateral epicondyle of the femur, 3) the lateral malleolus of the fibula, and 4) the base of the fifth

metatarsal. Each participant was then instructed to walk across a force platform at a self-selected pace for three separate trials.

Kinematic data were captured at 30 Hz with a Canon 3CCD digital video camcorder (GL2 NTSC; Canon, Lake Success, New York) positioned 6.0 m from the sagittal plane of motion of the participant for each walking trial. Recorded video was saved and analyzed offline using Ariel Dynamics Performance Analysis System software (Ariel Dynamics Inc, Trabuco Canyon, California). The video was digitized, and the data exported for analysis included stride length, peak ankle angle during the swing phase (θ_{ASW}), ankle angle at heel contact, knee angle at heel contact, ankle angle at toe-off, knee angle at toe-off, ankle angle at the beginning of the double stance phase, and knee angle at the beginning of the double stance phase. Stride length was determined by the ankle position difference in the anteroposterior direction of the sagittal plane from right heel contact to subsequent right heel contact. Joint angles were extracted from the video using Ariel Dynamics Performance Analysis System software. The ankle and knee angles at the beginning of the double stance phase were recorded for the right ankle when the left leg made heel contact; therefore, this was the end of single-leg support for the right foot and the beginning of double-leg support.

Kinetic data, normalized to body weight, were collected at 1,000 Hz using an AMTI force platform (OR6-7 1000; Advanced Medical Technology Inc, Watertown, Massachusetts) and were amplified (MiniAmp MSA-6; Advanced Medical Technology Inc). Kinetic data were extracted using AMTI NetForce software (Advanced Medical Technology Inc). Data of interest included maximal vertical ground reaction force ($F_{ZHC \text{ max}}$), anteroposterior force ($F_{YHC \text{ max}}$), and mediolateral ground reaction force ($F_{XHC \text{ max}}$) at heel contact (Fig. 1A). Also collected was maximal braking impulse ($J_{YB \text{ max}}$), maximal propulsive impulse, and stance time. The $F_{ZHC \text{ max}}$ and corresponding F_Y were used to calculate the attack angle (Fig. 1B).

Statistical Analysis

A mixed factorial 2 (sex) $\times$ 2 (footwear) repeated-measures analysis of variance for each dependent variable was conducted for statistical analysis of the data. The software used was SPSS 16.0 for Windows (SPSS Inc, Chicago, Illinois). An $\alpha < 0.05$ was used for statistical significance.

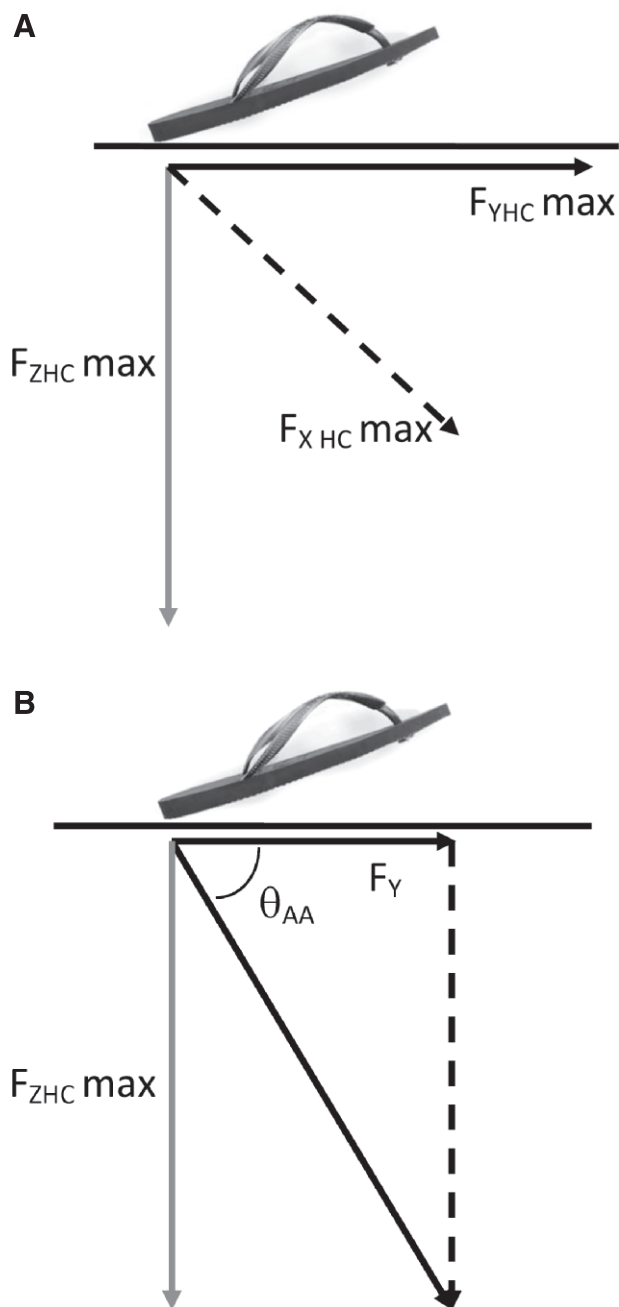


Figure 1. A, Representation of maximal vertical ($F_{ZHC \text{ max}}$), mediolateral ($F_{XHC \text{ max}}$), and anteroposterior ($F_{YHC \text{ max}}$) force at heel contact. B, Representation of construction of the attack angle (θ_{AA}).

Results

Kinematics

The results of this study show a significant main effect of footwear on stride length ($F_{1,54} = 6.807$, $P = .012$), with sneakers having a longer stride length than flip-flops. Another significant effect of footwear

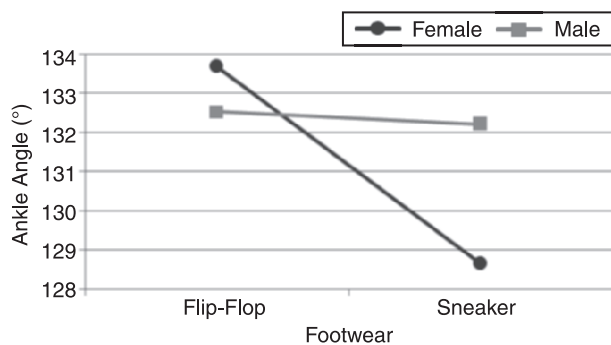


Figure 2. Interaction effect of footwear and sex on peak ankle angle during the swing phase ($F_{1,54} = 4.093$, $P = .048$, $\eta^2 = 0.089$, power = 0.618).

was found on ankle angle at the beginning of the double stance phase ($F_{1,54} = 22.876$, $P < .001$), with flip-flops resulting in an increased ankle angle/plantarflexion compared with sneakers at the beginning of the double support phase. There was also a significant interaction effect of footwear and sex on θ_{ASW} ($F_{1,54} = 4.093$, $P = .048$), with men demonstrating a similar mean θ_{ASW} for sneakers (132.22°) and flip-flops (132.54°) and females demonstrating a larger mean θ_{ASW} while wearing flip-flops (133.68°) than sneakers (128.66°) (Fig. 2). In addition, there was a simple main effect of footwear on θ_{ASW} that indicated that dorsiflexion decreased during the swing phase while wearing flip-flops (Table 1).

Kinetics

Results indicated a significant main effect of footwear (Table 1) and sex ($F_{1,53} = 26.940$, $P < .001$) on J_{YB} max.

For J_{YB} max, men had a mean of $114.0 \text{ N} \times \text{sec}$ and women had a mean of $86.1 \text{ N} \times \text{sec}$. This finding indicates that men had greater braking impulse than did women. There was a significant main effect of sex on maximal propulsive impulse ($F_{1,54} = 65.434$, $P < .001$). Men had a larger mean J_{XP} max versus women ($392.6 \text{ N} \times \text{sec}$ versus $269.1 \text{ N} \times \text{sec}$), indicating that men had a larger propulsive impulse than did women.

Analysis also demonstrated a significant main effect of footwear on stance time ($F_{1,54} = 5.480$, $P = .023$), with sneakers producing a longer stance time (Table 1), and of sex ($F_{1,54} = 31.169$, $P < .001$) on stance time. Closer analysis indicated that men had a longer mean stance time (0.728 sec) than did women (0.645 sec).

There was a significant main effect of sex on F_{ZHC} max ($F_{1,54} = 45152.8$, $P < .001$), with men having a larger mean F_{ZHC} max (861.5 N) compared with women (672.9 N). Furthermore, a significant interaction effect of footwear and sex on F_{YHC} max was found ($F_{1,54} = 9.642$, $P = .003$) (Fig. 3). Men had a larger mean F_{YHC} max while wearing flip-flops (149.1 N) versus sneakers (141.0 N); women had a larger mean F_{YHC} max while wearing sneakers (126.7 N) versus flip-flops (116.2 N). There was a significant simple main effect of sex on F_{YHC} max ($F_{1,54} = 9.695$, $P = .003$), with men having a larger mean F_{YHC} max (145.0 N) than women (121.4 N).

The study showed a significant interaction effect of footwear and sex on attack angle ($F_{1,54} = 4.313$, $P = .043$) (Fig. 4). Women had a greater mean attack angle while wearing flip-flops (82.19°) versus sneakers (81.39°), whereas men had a greater mean value

Table 1. Results of the Effect of Footwear on Kinetic and Kinematic Variables^a

Variable	Footwear	Mean	SD	F	P Value	η^2	Power
SL (m)	Flip-flops	1.8750	0.1963	6.807	.012	0.112	0.727
	Sneakers	1.9310	0.1468				
θ_{ADB} (°)	Flip-flops	106.31	6.20	22.876	<.001	0.298	0.997
	Sneakers	102.08	5.24				
θ_{ASW} (°)	Flip-flops	133.11	5.94	5.294	.025	0.089	0.618
	Sneakers	130.44	8.08				
J_{YB} max (N × sec)	Flip-flops	93.902	23.842	4.941	.031	0.085	0.588
	Sneakers	97.550	23.353				
ST (sec)	Flip-flops	.66802	0.067028	5.480	.023	0.092	0.633
	Sneakers	.67862	0.068920				

Abbreviations: θ_{ADB} , ankle angle at the beginning of the double stance phase; θ_{ASW} , peak ankle angle during the swing phase; J_{YB} max, maximal braking impulse; SL, stride length; ST, stance time.

^aAll of the variables are based on 56 participants except J_{YB} max, which is based on 55 participants. All of the variables are statistically significant ($P < .05$).

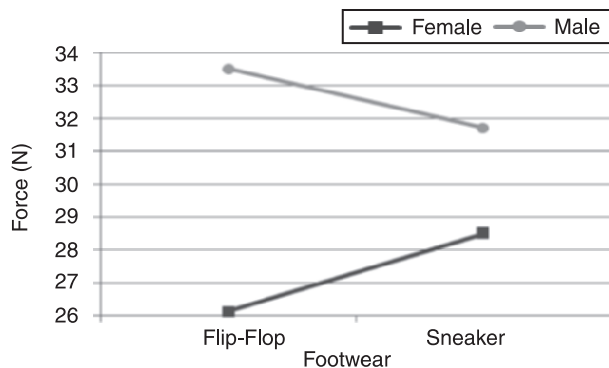


Figure 3. Interaction effect of footwear and sex on maximal anteroposterior force at heel contact ($F_{1,54} = 9.642$, $P = .003$, $\eta^2 = 0.152$, power = 0.862).

while wearing sneakers (81.90°) versus flip-flops (81.66°).

Discussion

Human gait and the effect of different types of footwear on gait patterns have been studied extensively⁸⁻¹¹; however, there has been no scientific research to date, to our knowledge, on the effects of thong-style flip-flops on gait. One study⁵ has investigated the varying plantar pressures experienced in barefoot, flip-flop, and athletic shoe conditions and found that flip-flops yielded greater plantar pressures than did athletic shoes, but no specific conclusions were made regarding gait alterations. The results of the present study demonstrate that gait is altered while wearing thong-style flip-flops compared with sneakers and that the changes in gait are different for men and women. Significant interactions between sex and footwear were noted for ankle angle during the swing phase, attack angle

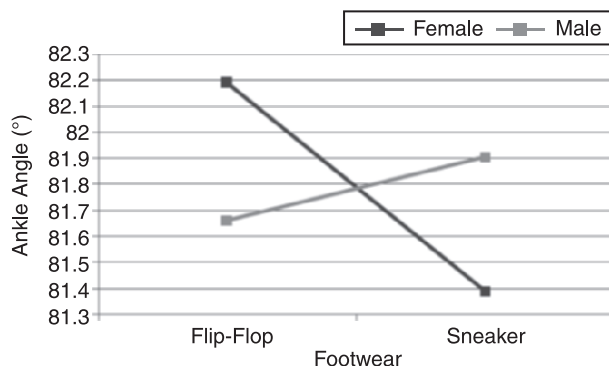


Figure 4. Interaction effect of footwear and sex on attack angle at heel contact ($F_{1,54} = 4.313$, $P = .043$, $\eta^2 = 0.074$, power = 0.532).

at heel contact, and peak anterior force. Significant differences between thong-style flip-flops and sneakers were noted for stride length, θ_{ADB} , θ_{ASW} , and stance times. Significant differences between men and women include braking and propulsive impulse, peak anterior force, and peak vertical force.

Previous research comparing barefoot walking with walking in shoes has demonstrated that barefoot walking yields smaller stride lengths.^{8, 9} In one study,⁸ gait characteristics of individuals wearing slippers and walking barefoot were similar. If it is accepted that thong-style flip-flops are somewhat comparable with slippers, the present study supports these previous findings in that significant decreases in stride length while wearing flip-flops were observed. One possible explanation for the decreased stride length with flip-flops could be the decreased mass of the flip-flop versus the shoe, resulting in a decreased distal mass leading to decreased inertia during the swing phase, as postulated by Majumdar et al.⁸ Anecdotally, just before heel strike, it is customary for a walker to swing the foot past the floor and then draw the heel to the floor; however, while wearing flip-flops this movement would be contraindicated to keeping the flip-flop on the foot, thus demanding that the forward swing of the leg be shortened to prevent the flip-flop from leaving the foot.

Larger braking impulses were observed while wearing sneakers; however, there were no differences observed in propulsive impulses. The larger braking impulse is attributed to the longer stance time during the sneaker condition because there was no significant difference between forces across the period. At this time, it is unclear why the sneaker condition provided for longer stance times or why the flip-flop condition yielded shorter stance times. It is proposed that the toe flexion noted anecdotally in preparation for toe-off may act to “pull” the foot into heel-off more rapidly than is experienced in the sneaker condition. In addition, the longer stride lengths noted while wearing sneakers would seem to require a greater braking impulse to bring the foot to rest before receiving the full weight of the body.

Note that there were no statistically significant differences in the joint angles at heel contact or toe-off for either the knee or ankle angle; however, significant differences were found in ankle angle during the swing phase of the nonsupport leg and at the beginning of the double support phase. When wearing thong-style flip-flops, the plantarflexion angle during the swing phase increased. It is reasonable to conclude that this decrease in dor-

siflexion can be attributed to contraction of the flexor digitorum longus and flexor hallucis longus in an attempt to use the phalanges to grip the flip-flop and prevent the flip-flop from coming off the foot. Because the flexor digitorum longus and flexor hallucis longus muscles cross the ankle joint, once the phalanges are flexed they will contribute to an implied ankle plantarflexion moment. Electromyography of the toe flexors was not recorded in this study; however, this should be included in future research evaluating flip-flops.

Also, research has been conducted to suggest that chronic lower back pain may be affected by the function of the metatarsophalangeal joints in the foot.¹² Limited range of motion or function in the first metatarsophalangeal joint has been labeled functional hallux limitus.¹³ During normal gait, metatarsophalangeal joint function plays a large role in preparation of the stance leg for the swing phase. As the body's center of mass passes over the stance leg, the ankle plantarflexes and the metatarsophalangeal joint extends to allow for optimal hip extension. This hip extension puts the hip flexors, such as the iliopsoas, on stretch and aids in the proceeding hip flexion by eliciting the elastic properties of the muscular skeletal system. Dananberg et al.^{12, 13} suggest that functional hallux limitus does not allow for proper metatarsophalangeal joint extension and, therefore, results in decreased hip extension. The decreased hip extension does not elicit the contribution of the elastic properties of the hip flexors for limb advancement; therefore, the hip flexors are susceptible to overuse injuries and may result in chronic low-back pain. Dananberg and Guiliano¹² also found that by using custom orthotic devices and manipulating foot motion, chronic back pain symptoms could be decreased more than with conventional medical practices. This study did not measure metatarsophalangeal joint motion, but because the phalanges are fixed on the ground during the beginning of the double support phase, we speculate that the increased plantarflexion resulted in increased metatarsophalangeal joint extension. One explanation for the increased metatarsophalangeal joint extension is that flip-flops generally have a more compliant footbed and sole; therefore, the function of the metatarsophalangeal joint is not hindered by the opposition of the footwear.

Statistically significant differences were noted between the sexes. Kinetically, men produced a larger normalized braking impulse, propulsive impulse, F_{ZHC} max, and F_{YHC} max. These findings

support the literature in that there are observable differences in gait kinetics and kinematics between males and females.¹⁴⁻¹⁶ Although there were differences between the sexes in several of the kinetic variables, there were no statistically significant differences for joint angles in the sagittal plane during the stance phase, thus supporting the work of Ferber et al.¹⁵

This preliminary investigation has some primary limitations, including the absence of electromyography, the variety of footwear brands used, the absence of hip and metatarsophalangeal joint angles, the variability in the wear of the footwear, the sample population, and the decision to consider only 2-D parameters. Electromyography measures could have provided critical insights into abnormal coordination of muscles and increased activity of lower-leg musculature during flip-flop wear compared with sneaker wear. Future research should include metatarsophalangeal joint and coxofemoral joint kinematics to investigate whether flip-flops result in limited range of motion at these joints and may play a similar role in chronic back problems associated with functional hallux limitus. In addition, although the participants all had thong-style flip-flops and athletic sneakers, there are various brands of each type of footwear. The degradation of the footwear provided by the participants was not controlled. Future research should be limited to one brand and model for each type of footwear that is new, the same age, or has been worn for the same duration. This will control for varying materials of the footwear and the degradation of said materials. The age group for this study was 19- to 25-year-old college students; therefore, the conclusions drawn from this study should be applied only to this age group and should not be extrapolated to other age groups. Future research should include a wider age range for the sample. Also, although the parameters considered are appropriate for a 2-D analysis, a 3-D analysis would provide valuable information regarding the more complex movements of the foot, particularly in the transverse plane.

Therefore, the present study concludes that in individuals aged 19 to 25 years, wearing thong-style flip-flops results in a gait pattern that differs from that seen in individuals walking in sneakers. The different gait parameters shown in the present research provide insight into the causes of foot, ankle, and lower-leg discomfort associated with the use of flip-flops but do not show causation. Further kinetic, kinematic, and electromyographic research is needed to compare walking in flip-flops versus other types of

footwear and walking barefoot; this research is being conducted at Auburn University.

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References

1. WILSON C: Men are toeing the sandal line. USA Today. April 18, 2004: Lifestyle.
2. No slowing down for surf industry. SIMA Web site. Available at: <http://www.sima.com/news-information/news-detail/id/25.aspx>. Accessed June 6, 2008.
3. DASH J: The flap over flip-flops: latest foot fashion is dividing more than toes in the office. Baltimore Business Journal. Published June 30, 2006.
4. Popular flip-flop sandals linked to rising youth heel pain rate. American College of Foot and Ankle Surgeons Website. Available at: <http://www.acfas.org/Media/Content.aspx?id=103>. Accessed January 16, 2008.
5. CARL TJ, BARRETT SL: Computerized analysis of plantar pressure variation in flip-flops, athletic shoes, and bare feet. JAPMA **98**: 374, 2008.
6. PETTITT R, DOLSKI A: Corrective neuromuscular approach to the treatment of iliotibial band friction syndrome: a case report. J Athl Train **35**: 96, 2000.
7. RENNE JW: The iliotibial band friction syndrome. J Bone Joint Surg Am **57**: 1110, 1975.
8. MAJUMDAR D, BANERJEE PK, MAJUMDAR D, ET AL: Temporal spatial parameters of gait with barefoot, bathroom slippers and military boots. Indian J Physiol Pharmacol **50**: 33, 2006.
9. OEFFINGER D, BRAUCH B, CRANFILL S, ET AL: Comparison of gait with and without shoes in children. Gait Posture **9**: 95, 1999.
10. SCHAFF PS, CAVANAGH PR: Shoes for the insensitive foot: the effect of a "rocker bottom" shoe modification on plantar pressure distribution. Foot Ankle **11**: 129, 1990.
11. KURZ MJ, STERGIOU N: The spanning set indicates that variability during the stance period of running is affected by footwear. Gait Posture **17**: 132, 2003.
12. DANANBERG HJ, GUILLANO M: Chronic low-back pain and its response to custom-made foot orthoses. JAPMA **89**: 109, 1999.
13. DANANBERG HJ: Functional hallux limitus and its relationship to gait efficiency. JAPMA **76**: 648, 1986.
14. KERRIGAN DC, TODD MK, DELLA CROCE U: Gender differences in joint biomechanics during walking: normative study in young adults. Am J Phys Med Rehabil **77**: 2, 1998.
15. FERBER R, DAVIS IM, WILLIAMS DS III: Gender differences in lower extremity mechanics during running. Clin Biomech (Bristol, Avon) **18**: 350, 2003.
16. CHO SH, PARK JM, KWON OY: Gender differences in three dimensional gait analysis data from 98 healthy Korean adults. Clin Biomech (Bristol, Avon) **19**: 145, 2004.