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Lower Extremity Joint Kinematics of Shod, Barefoot, and Simulated Barefoot Treadmill Running

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ABSTRACT

International Journal of Exercise Science 11(1): 717-729, 2018. Barefoot running is considered to decrease injury risk, but is not always practical, particularly while running on a fitness center treadmill. The purpose of this study was to compare the kinematics of shod, barefoot, and simulated barefoot running. Twelve subjects (age = 21.1 ± 1.2 years) who regularly run on a treadmill for fitness participated in the study. After a warm up, each runner ran on a Biodex RTM 400 treadmill set at 7.4 mph (approximately 3.3 m/s) in their own shoes, barefoot, and while running "like they were barefoot" in their own shoes. Sixteen reflective markers were affixed to each subject to use PlugInGait (Vicon) to determine three-dimensional body landmark coordinates and to compute lower extremity joint angles. Values at touchdown and during stance were averaged over ten strides for analysis. Repeated measures ANOVA was implemented to determine differences based on running condition ($p < 0.05$) and post hoc testing was performed with an adjustment for multiple comparisons ($p<0.05/3$). At touchdown, ankle angle values significantly differed based on condition (6.2 ± 5.9° vs. -4.0 ± 12.0° vs, -0.2 ± 13.3°; $p = 0.004$ for shod, barefoot and simulated barefoot running, respectively) indicating that when simulating barefoot running the subjects altered their foot strike pattern. Stride frequency differed between shod and barefoot running (1.415±0.068 Hz vs. 1.457±0.065 Hz; $p = 0.001$) but the simulated barefoot condition did not differ from the shod condition. The runners were able to simulate an important element of barefoot running, but they did not completely mimic their barefoot running pattern.

KEY WORDS: Foot strike pattern, running injuries, stride length, stride frequency

INTRODUCTION

Arguments have been made that our bodies are not meant to run shod and that the invention of the well cushioned running shoe has been detrimental to runners' bodies (21, 22, 28). Barefoot running is thought to encourage mechanics that lessen injury risk which has been reported to range from 19 – 79% and does not appear to be decreasing over time (17, 36). According to the National Sporting Goods Association, approximately 45 million people in the United States run on a regular basis (26). Due to the large numbers of individuals potentially affected, it is important to better understand what may be done to decrease the high injury occurrence.

The magnitude and loading rate of vertical ground reaction forces have been related to several common running injuries. Large loading rates, both maximum instantaneous and average, have been associated with lower-limb stress fractures (10, 25) and plantar fasciitis (29). Cheung and Davis (2) performed a training intervention in runners with patellofemoral pain and reported that a decrease in pain values and an increase in functionality scores were linked with decreases in instantaneous and average loading rates and vertical impact peak forces. Research related to the relationship between injury and the maximum vertical ground reaction force exerted on the body during running are mixed. Zadpoor and Nikooyan (39) reported that for runners who have experienced stress fractures, the maximum vertical ground reaction force has been found to be significantly larger, nonsignificantly larger, or smaller than those who have not. Pohl et al. (29) reported a trend towards the force being larger in subjects who had previously had plantar fasciitis.

Running barefoot has been reported to decrease these force magnitudes and loading rates by some researchers (8, 14, 22). However, some of these results indicate that the footstrike pattern determines whether or not these forces are diminished by running barefoot (3, 22). In particular, Shih et al. (31) instructed runners to use a rearfoot striking pattern or a forefoot striking pattern while running barefoot and while running shod. They concluded that using a forefoot striking pattern decreased the loading rate for both shod and barefoot conditions, but that based on the loading rate, that the combination of rearfoot striking and barefoot running increased injury risk. Similarly, Tam et al. (33) noted that the loading rate for barefoot running was actually greater than the loading rate while shod for some of their subjects. They further noted that this subset of runners had a larger dorsiflexion angle at touchdown and thus were likely using a rearfoot striking pattern.

Force magnitudes or loading rates have also been found to decrease when a shorter stride length (or inversely a greater stride frequency if the velocity is constant) is used (16, 35). Edwards et al. (9) concluded that a 10% reduction in stride length would result in a decrease in stress fracture risk, despite the increase in the number of impacts. Barefoot running has been found to induce a shorter stride length which may decrease shock attenuation forces, and therefore injury risk (24).

Running in minimalist shoes has not been deemed a suitable substitution for either shod or barefoot running. Guiliani et al. (13) reported that minimalist shoes were associated with stress fractures in metatarsal bones of runners who changed from traditional running shoes to minimalist shoes. Willy and Davis (38) compared shod to minimalist shoe running and reported peak vertical impact force and average loading rates were larger in the minimalist shoes. Along with these differences, they noted no changes in the stride length or stride rate which are often found to be altered when changing from shod to barefoot running.

The combination of using a shorter stride length and a midfoot or forefoot striking pattern seems desirable for decreasing injury risk. However, the two are not inextricably linked but do seem common when running barefoot. It may be easier to instruct subjects to run as if they were barefoot rather than give multiple instructions, especially if the subjects are not trained runners.

The sizable population of runners who run on treadmills solely for fitness is typically not considered in running research. In 2015, approximately 44% of health club members in the United States (about 24.2 million people) indicated using a treadmill (18). Adopting barefoot running for these runners is not practical, even if it was advantageous. Fitness clubs and gyms are not going to allow barefoot running due to the possibility that their clientele might be injured more easily if running on a treadmill barefoot. Along with the potential injury, there are hygienic reasons why it would be unwise to be barefoot in a fitness facility. Giving instruction on using a particular foot strike pattern and stride length may not be effective for this population due to them not being as tuned into their specific mechanics, unlike trained runners. However, because many of the desired changes come about when running barefoot, it may be possible to simply instruct these individuals to simulate barefoot running. The purpose of this study was to compare the kinematics of shod, barefoot and simulated barefoot running in recreational treadmill runners.

METHODS

Participants

Twelve recreationally active college students (6 males and 6 females) participated in this study. Individuals were eligible for participation if they regularly ran on a treadmill for exercise. Additionally, they needed to be in good health and injury-free for the past year to be eligible. None of the participants wore orthotics or shoes designed to alter foot contact. Participants did not wear minimalist shoes, shoes designed for runners with a particular foot strike (e.g. forefoot runners) or shoes that correct for undesired foot strike (e.g. over-pronating). The mean age, height and body mass of the subjects were 21.1 ± 1.2 years, 1.66 ± 0.63 m, and 65.8 ± 10.0 kg, respectively. Once each participant read and signed the consent form approved by the California Lutheran University Institutional Review Board, they filled out a health and activity questionnaire. The questionnaire ensured that they were injury-free and had not experienced any past injury that might alter their kinematics (e.g. ACL reconstruction). Information regarding the range of typical training speeds for each participant was gathered to ensure that the running pace selected for the study was appropriate and comfortable for each participant. During testing, subjects were also asked to confirm that the chosen speed was comfortable for them.

Protocol

All participants performed a four-minute warm up on the Biodex RTM 400 treadmill (Biodex, Shirley, NY) at a self-selected pace. After this, several anthropometric measurements were taken for the lower body PlugInGait model (Vicon, Oxford, United Kingdom) including the length of each leg (anterior superior iliac spine to medial malleolus), each knee width and each ankle width. Then sixteen reflective markers were affixed to the following body landmarks on each side of the body: anterior superior iliac spine, posterior superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, lateral malleolus, posterior calcaneus (heel), and second metatarsal head (toe) (19). For shod trials, the markers for the posterior calcaneus and second metatarsal were placed directly on the shoe, over the landmark.

Participants ran on the treadmill in three different conditions with a two-minute rest between the three conditions. The first condition consisted of subjects running in their own shoes at 7.4 mph (approximately 3.3 m/s). Prior to any trials being collected, a static trial was collected. Participants then stepped onto the stationary treadmill and increased the speed until the desired speed of 7.4 mph was obtained. Investigators waited until a consistent movement pattern was achieved and then asked the participant for confirmation that they were comfortable running at this speed. Once this was confirmed, motion capture data were collected for one minute to obtain data for the shod condition. After this trial, the participants took off their shoes and reflective markers were placed directly on their right and left posterior calcaneus and second metatarsal. A second static trial was collected. As before, once a consistent movement pattern was achieved and participant comfort confirmed, participants then ran barefoot for one minute to create the barefoot running condition. Lastly, the two reflective markers directly on each foot were removed and the subjects' running shoes were put back on for a third trial. The reflective markers on the shoes were not altered from the original shod trial. A static trial was collected prior to this final running condition. For this trial, the participants were asked to "run as if you were barefoot" to create a simulated barefoot running condition. As with the other two conditions, motion capture data were collected for one minute after a consistent movement pattern was observed and participant comfort was confirmed.

During each data collection, a system of six Vicon MX40 cameras were used to capture three-dimensional coordinates of the markers (Vicon, Oxford, United Kingdom) at 120 Hz. Marker data were filtered using a 4th order Butterworth filter with a cutoff frequency of 10 Hz. Joint angle data were computed using Nexus 1.8.5. The instants of foot touchdown and takeoff were determined using the methodologies recommended by Leitch et al. (20) for runners with both rear foot and midfoot striking patterns. The method for identifying foot touchdown was based on O'Connor et al. (27) and used the average of the heel and toe markers to represent the foot. Touchdown corresponded to a local minimum of the vertical velocity of the foot within a window around the minimum foot position. The method for identifying foot takeoff was based on De Witt (6). Foot takeoff was determined to be the local maximum of the vertical acceleration of the toe between the time of touchdown and the maximum vertical position for the toe.

Joint angles were calculated using PlugInGait. Positive angles in the sagittal plane indicated that the hip was flexed, the knee was flexed, and the ankle was dorsiflexed. Positive angles in the frontal plane indicated that the hip was adducted, the knee was adducted (varus), and the ankle was inverted. Values analyzed included the sagittal and frontal plane hip, knee and ankle angles at right foot touchdown. During stance, the extreme angle values were determined for each joint in both planes and the corresponding joint range of motion (ROM) was computed. Stride frequency and stride length were computed using the frame numbers and the relationship between the fixed treadmill velocity and the computed stride time. Stance time (contact time) and swing phase time (both absolute and as a percentage of a stride) were also determined. All data values for analysis were computed for the right leg for ten consecutive strides and averaged over the ten strides.

Statistical analysis

Repeated measures ANOVA was used to determine if there was a difference in means between the three running conditions (shod, barefoot, and simulated barefoot) with significance set with $p < 0.05$. Partial eta squared (η_p^2) was calculated to determine effect size. If a significant main effect was identified, post hoc analysis was performed using Least Significant Difference (LSD). To correct for the multiple comparisons being made between pairs of conditions, a Bonferroni adjustment was made and an adjusted alpha level of 0.05/3 was used to determine significance for any pairwise comparison. SPSS for IBM Version 25 (Chicago, IL) was used for all statistical analysis.

RESULTS

Table 1 provides sagittal and frontal plane values for the hip, knee and ankle joints at touchdown (TD). There was not a significant main effect of running condition on the hip joint and knee joint flexion angles at touchdown. However, there was a significant main effect of running condition on the sagittal plane ankle angle at touchdown ($p = 0.004$; $\eta_p^2 = 0.399$). In particular, the angle was significantly different between the shod and barefoot conditions ($p = 0.007$) with the ankle being dorsiflexed in the shod condition and plantarflexed in the barefoot condition. There was no significant difference between the ankle angle values at touchdown between simulated barefoot and barefoot conditions. In the frontal plane, there were no main effects of running condition on the hip, knee or ankle joints at touchdown.

Table 1. Mean and standard deviation joint angle values in the sagittal and frontal planes for the three conditions at touchdown and the p-value for any significant main effect identified with repeated measures ANOVA ($p < 0.05$).

Variable	Shod	Barefoot	Simulated	p-value
Hip Flexion (°) at TD	33.0±5.2	31.9±5.7	31.8±5.9	NS
Knee Flexion (°) at TD	14.4±4.0	14.4±3.7	14.8±3.8	NS
Ankle Dorsiflexion(+) /Plantarflexion (-) at TD (°)[a]	6.2±5.9	-4.0±12.0	-0.2±13.3	0.004
Hip Adduction at TD (°)	5.1±5.1	3.8±5.4	4.5±6.1	NS
Knee Varus(+)/Valgus (-) at TD (°)	-1.4±3.5	-0.9±3.3	-0.7±3.4	NS
Ankle Inversion(+)/Eversion (-) at TD (°)	-1.2±1.7	1.5±5.1	0.5±5.1	NS

Note: [a] Significant difference between shod and barefoot, [b] Significant difference between shod and simulated barefoot, [c] Significant difference between barefoot and simulated barefoot, NS indicates no significant difference. Significance was set at $p < 0.05/3$ to correct for multiple comparisons.

Extreme values during stance for each joint in the sagittal and frontal planes are given in Table 2. There was a main effect of running condition on the maximum hip flexion angle during stance ($p = 0.024$; $\eta_p^2 = 0.287$). The maximum hip flexion angle was significantly larger when running shod compared to both the running barefoot condition ($p = 0.010$) and the simulating barefoot running condition ($p = 0.014$). There was also a main effect of running condition on the maximum hip extension angle during stance ($p = 0.002$; $\eta_p^2 = 0.424$). The maximum hip extension angle was significantly smaller when running shod compared to both running barefoot ($p = 0.015$) and simulating barefoot running ($p = 0.006$). There was no main effect of running condition on the hip's ROM during stance.

There was a main effect of running condition on the maximum knee flexion angle during stance ($p < 0.001$; $\eta_p^2 = 0.799$). In particular, subjects' maximum knee flexion angles were significantly smaller when running barefoot when compared to both running shod ($p = 0.001$) and simulating barefoot running ($p < 0.001$). Additionally, the subjects' maximum knee flexion angle was significantly smaller when simulating barefoot running when compared to running shod ($p = 0.013$). There was no main effect of running condition on the minimum knee flexion angle during stance. There was a main effect of running condition on the corresponding knee ROM value ($p < 0.001$; $\eta_p^2 = 0.704$). The knee flexion ROM was significantly smaller for the barefoot running condition when compared to the shod condition ($p < 0.001$) and the simulated barefoot running condition ($p < 0.001$).

There was a main effect of running condition on the maximum dorsiflexion angle during stance ($p = 0.040$; $\eta_p^2 = 0.254$). The barefoot running condition had a significantly larger maximum dorsiflexion angle than the simulated barefoot running condition ($p = 0.016$). There was a main effect of running condition on the maximum plantarflexion angle during stance ($p = 0.001$; $\eta_p^2 = 0.450$). The barefoot running condition had a significantly larger maximum plantarflexion angle than both the shod running condition ($p = 0.006$) and the simulated barefoot running condition ($p = 0.006$). There was a main effect of running condition on the corresponding ankle ROM ($p < 0.001$; $\eta_p^2 = 0.651$). The barefoot running condition had a significantly larger ROM than both the shod condition ($p = 0.001$) and the simulated barefoot running condition ($p < 0.001$).

There were no significant main effects of running condition on the frontal plane angles (maximum, minimum, and ROM) for the hip, knee or ankle joints.

Table 2. Mean and standard deviation extreme joint angle values in the sagittal and frontal planes for the three conditions during stance and the p-value for any significant main effect identified with repeated measures ANOVA ($p < 0.05$).

Variable	Shod	Barefoot	Simulated	p-value
Maximum Hip Flexion (°)[a,b]	33.6±5.6	32.1±5.8	32.2±6.3	0.024
Maximum Hip Extension (°)[a,b]	-13.1±5.7	-14.0±6.0	-14.4±5.6	0.002
Hip Flexion ROM (°)	46.7±4.2	46.1±3.8	46.7±5.0	NS
Maximum Knee Flexion (°)[a,b,c]	43.6±3.9	40.1±4.6	42.5±4.1	<0.001
Minimum Knee Flexion (°)	8.9±5.9	9.0±4.6	8.7±5.8	NS
Knee Flexion ROM (°)[a,c]	34.6±6.0	31.1±5.4	33.8±6.3	<0.001
Maximum Ankle Dorsiflexion (°)[c]	22.7±3.7	23.1±4.8	21.2±5.1	0.040
Maximum Ankle Plantarflexion (°)[a,c]	-30.8±10.2	-36.1±9.4	-32.5±9.1	0.001
Ankle Dorsiflexion ROM (°)[a,c]	53.6±9.7	59.1±10.7	53.8±8.9	<0.001
Maximum Hip Adduction (°)	10.7±6.3	10.5±6.4	10.2±6.6	NS
Maximum Hip Abduction (°)	-3.0±4.0	-3.0±4.5	-3.2±4.5	NS
Hip Adduction ROM (°)	13.7±3.6	13.5±3.3	13.4±3.5	NS
Maximum Knee Varus (°)	1.5±4.3	1.6±4.4	1.7±4.4	NS
Maximum Knee Valgus (°)	-6.4±4.3	-6.0±4.3	-7.5±5.3	NS
Knee Varus ROM (°)	7.9±2.1	7.5±2.7	9.1±3.4	NS
Maximum Ankle Inversion (°)	14.8±8.8	17.0±9.3	14.5±8.9	NS

Maximum Ankle Eversion (°)	-2.0±2.3	-1.6±2.3	-2.2±2.1	NS
Ankle Inversion ROM (°)	16.8±10.4	18.6±11.0	16.7±10.6	NS

Note: [a] Significant difference between shod and barefoot, [b] Significant difference between shod and simulated barefoot, [c] Significant difference between barefoot and simulated barefoot, NS indicates no significant difference. Significance was set at $p < 0.05/3$ to correct for multiple comparisons

Table 3 provides values associated with stride frequency and length, as well as contact and swing times. There was a main effect of running condition on the stride frequency ($p < 0.001$; $\eta_p^2 = 0.619$) with the barefoot condition having a significantly greater stride frequency than both the shod condition ($p < 0.001$) and the simulated barefoot condition ($p = 0.001$). There was a main effect of running condition on the stride length ($p < 0.001$; $\eta_p^2 = 0.624$) with the barefoot condition having a significantly shorter stride length than both the shod condition ($p < 0.001$) and the simulated barefoot condition ($p = 0.001$). There was a main effect of running condition on the ground contact time ($p = 0.012$; $\eta_p^2 = 0.329$). However, post hoc testing did not reveal any significant pairwise differences. There were no main effects of running condition on the percent contact time, swing time, or percent swing time.

Table 3. Mean and standard deviation stride frequency and timing values for the three conditions and the p-value for the ANOVA comparing the three conditions.

Variable	**Shod**	**Barefoot**	**Simulated**	**p-value**
Stride frequency (Hz) [a,c]	1.415±0.067	1.457±0.066	1.428±0.060	< 0.001
Stride length (m) [a,c]	2.343±0.112	2.275±0.105	2.320±0.100	< 0.001
Contact time (s)*	0.255±0.015	0.244±0.015	0.252±0.016	0.012
Swing time (s)	0.453±0.040	0.444±0.031	0.450±0.032	NS
Percent contact time (%)	36.17±3.17	35.52±2.32	35.93±2.64	NS
Percent swing time (%)	63.83±3.17	64.48±2.32	64.07±2.64	NS

Note: [a] Significant difference between shod and barefoot, [b] Significant difference between shod and simulated barefoot, [c] Significant difference between barefoot and simulated barefoot, NS indicates no significant difference. *Indicates that while the ANOVA found significant differences, the post hoc testing did not identify a pair that was significantly different. Significance was set at $p < 0.05/3$ to correct for multiple comparisons.

DISCUSSION

The aim of this study was to compare the kinematics of shod, barefoot and simulated barefoot running. In particular, the goal was to determine how the mechanics of simulated barefoot running compared to both shod and barefoot running. The subjects were successful in making changes in their mechanics when asked to simulate barefoot running. While not completely changing their shod running style to fully mimic barefoot running, they did make some significant changes that are frequently associated with barefoot running. The most meaningful differences seen in the kinematics between the three running conditions were in the ankle angles. Other studies have reported a marked difference in ankle angle at touchdown when running barefoot compared to running shod on a treadmill (3, 11, 12, 31) and over ground (14, 22, 23, 33, 34). The current study found that at touchdown, the subjects had a plantarflexed ankle when barefoot and a dorsiflexed ankle when shod. When simulating barefoot running, subjects did not differ from barefoot running and had an ankle position that was fairly neutral at touchdown.

Interestingly, there were no other sagittal angle differences at touchdown found when comparing the three running conditions. Previous studies have found mixed results in the knee flexion angle at touchdown. Some studies have reported no difference (22, 35, 37) while others have reported differences (11, 31, 33). Those who reported differences found that the knee was more flexed at touchdown when running barefoot. The lack of hip angle differences at touchdown is not surprising and is consistent with other studies (11, 31, 34, 37). Because there was no hip or knee angle difference between shod and barefoot running, it is not surprising that when simulating barefoot running the subjects made no alterations to their hip or knee position at touchdown.

It should be noted that the lack of difference in hip and knee angles coupled with the change in ankle angle likely indicates a change in foot orientation with the ground. The change from dorsiflexed ankle when shod to plantarflexed ankle or neutral ankle when barefoot or simulating barefoot running suggests that the foot strike at touchdown was midfoot or forefoot striking when barefoot or when simulating barefoot running. Adopting a midfoot or forefoot striking pattern may be the key to injury prevention. Shih et al. (31) compared different foot strike position when subjects were shod and barefoot. They reported larger peak and average loading rates when subjects used rear foot strike when compared to forefoot strike. This larger peak and average rate is speculated to be responsible for tibial and lower extremity injury (22). Daoud et al. (4) performed a retrospective study and found that 74% of middle and long distance collegiate runners experienced a moderate or severe injury each year. Of these, those habitually using a rearfoot strike pattern were over twice as likely to experience a repetitive stress injury. It appears that avoiding a rearfoot strike pattern could be beneficial to avoiding large vertical force or large rates of force loading. Diebal et al. (7) determined that for some individuals with chronic exertion compartment syndrome who had run using a rearfoot striking pattern could decrease compartment pressures by utilizing a forefoot striking pattern. Additionally, they decreased their peak vertical force and vertical impulse. This might indicate that the current subjects decreased their risk for tibial and lower extremity injuries when running barefoot and when simulating barefoot running. When instructed to “run like they were barefoot” the subjects were successful in adopting the preferred foot strike used in barefoot running.

The ankle continued to be a source of differences between the conditions during stance. When barefoot, the maximum dorsiflexion angle was larger when compared to the simulated barefoot condition while the shod value was not different from either condition. The maximum plantarflexion angle was largest for the barefoot condition with the shod running condition having the smallest maximum and the simulated barefoot condition value being between the two other conditions’ values. The barefoot condition had the largest ankle range of motion during stance with the shod and simulated barefoot conditions being smaller and comparable. The greater range of motion for the barefoot condition was not related to the foot strike position, but rather the larger maximum dorsiflexion angle which was obtained during stance and the larger plantarflexion angle obtained near or at toe off. Larger ROM values when barefoot have been reported by other authors (32, 33). Additionally, Shih et al. (31) reported larger values for both barefoot runners instructed to land with a heel strike and those instructed to land with a forefoot strike. It appears that the range of motion is not dictated by the landing condition, rather subjects appear to absorb more with their ankle when running barefoot. In particular, if the range of motion between touchdown and the maximum dorsiflexion angle is considered, there were large differences in the values across conditions. Specifically, when considering that the ankle was dorsiflexed at touchdown when runners were shod, the dorsiflexion range of motion was, on average, 16.5°. This average value was 27.1° when barefoot due to the ankle being plantarflexed at touchdown and dorsiflexed a greater amount. The average simulated barefoot condition was 21.4° which was between the shod and barefoot values. It seems that the runners made changes in their foot strike position and then absorbed the early impact forces more greatly when barefoot and when simulating barefoot than when shod.

The maximum knee flexion angle during stance differed between all three running conditions. It was significantly smaller when running barefoot when compared to both shod and simulated barefoot running with the value during simulated barefoot running trials being between the two other running conditions. Several other studies have found that the knee is less flexed when running barefoot (1, 5, 11, 31). The minimum knee angle did not differ between running conditions. The knee range of motion was smaller when running barefoot than when shod or when simulating barefoot running. A smaller ROM finding is consistent with many other studies (11, 31, 32, 33).

The subjects' maximum hip joint flexion angle was larger when running shod than when running barefoot or when simulating barefoot running. Their maximum hip extension angle was smaller when running shod than when running barefoot or when simulating barefoot running. This combination led to running condition having no effect on the hip's ROM during stance. This finding agrees with results from Shih et al. (27) when considering comparisons made between runners using a heel strike and using a forefoot strike.

Stride length was altered when running in different conditions. The length was significantly less when running barefoot which agrees with previous research (1, 11, 30, 32, 34). When simulating barefoot running, the subjects did not alter their stride length from what they used when shod. Since the velocity was kept constant for all three running conditions, the stride length changes were coupled with inverse changes in stride frequency. There was a significantly greater frequency when running barefoot compared to both shod and simulated barefoot. Others have reported higher stride frequency with barefoot running including Shih et al. (31) who found a higher frequency when running barefoot, regardless of foot strike pattern. Greater stride length or step frequency have been linked to smaller peak vertical ground reaction forces and a greater percent of time in stance (15). The smaller forces may put the subjects at less risk of tibial stress fractures (25).

The subjects in the current study were not successful in decreasing stride length when simulating barefoot running. The significant decrease from shod to barefoot was only a 3% decrease. The previous research investigating the effect of stride length on forces altered the stride length by a greater amount (5% and 10%). It was noted that Hobara et al. (16) used a running velocity of 2.5 m/s because they stated that any faster and the subjects were unable to alter their stride frequency to the desired values (±15% and ±30%). The running velocity in the current study was approximately 3.3 m/s and so may not have presented the opportunity to decrease stride length while maintaining the velocity. A decrease in stride length, coupled with a constant velocity means an increase in stride frequency. Also, running on a treadmill may make challenging conditions for the runners to alter their stride length while staying on the treadmill.

The contact time did not differ between conditions, but the barefoot condition did have a smaller contact time than the shod condition which has been a common finding by researchers comparing barefoot to shod running (5, 8, 23). Other researchers have also reported no difference in contact time when running a comparable speed (11, 32). The simulated barefoot contact time was, on average, less than shod but greater than barefoot. This pattern of the simulated condition having values between the shod and barefoot conditions was continued with the swing times.

It should be noted that while the subjects adjusted their running mechanics when running barefoot or when simulating barefoot running, many characteristics of their running mechanics were unchanged. None of the twelve joint angle comparisons that were made in the frontal plane produced a main effect of running condition. However, in the sagittal plane, eight of the twelve comparisons resulted in a main effect for running condition. While post hoc testing made adjustments for multiple comparisons for a particular dependent variable, no adjustment was made for multiple dependent variable comparisons. If such an adjustment had been made, fewer statistical differences would have been noted and the subjects' mechanics would have been observed to be even less changed. The subjects maintained extremely consistent running patterns despite running conditions being changed. Perhaps with subjects who were less experienced running on the treadmill this result would have been different or if data had been collected prior to subjects confirming that they were comfortable.

Limitations of this study include the fact that forces were not directly collected during the running trials because an instrumented treadmill was not available. If in-ground force plates had been used, the number of strides that could be analyzed would be diminished greatly and may not give an accurate picture of what alterations are being made. Additionally, using in-ground force plates for this study would not be appropriate since the population being considered run on fitness center treadmills. Another limitation is that the results relate to changes that were made immediately after the subjects ran barefoot on the treadmill. Different results may occur if they were asked to simulate barefoot running without experiencing barefoot running immediately prior to simulating barefoot running. Finally, the heel marker during the shod and simulated barefoot running trials was not directly on the heel and this could have influenced the ankle angle if the heel moved within the shoe.

Future research should include giving subjects instructions on exactly what changes were desired. In particular, it would be interesting to see what changes could be made by this population if subjects were asked to alter their foot strike pattern and to shorten their stride length. The latter suggestion may require a slower velocity to be used to enable the subjects to adequately increase their stride frequency. A direct measurement of force over multiple strides would be beneficial to determining directly if the vertical forces and rate of these forces decreased. Finally, it would be interesting to determine if more experienced and competitive runners were able to also effectively simulate barefoot running.

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