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Original Research

Ankle-Knee Initial Contact Angle and Latency to Maximum Angle are Affected by Prolonged Run

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ABSTRACT

International Journal of Exercise Science 14(1): 33-44, 2021. The initial contact and midstance angles may influence injury risk. Previous literature has not assessed these angles under the influence of new footwear for a non-exhaustive prolonged run or the relationship between the angles. To assess lower extremity kinematic changes and the relationship between kinematic parameters at initial contact and midstance with prolonged running under the influence of different types of footwear. Twelve experienced, recreational runners (6 male; 6 female; 24.8 ± 8.4 years; 70.5 ± 9.3 kg; 174.1 ± 9.7 cm) ran for 31 minutes at a self-selected pace for three testing sessions wearing maximalist, habitual, and minimalist shoes. Sixteen anatomical retroreflective markers and seven tracking clusters were placed on the participants' lower extremities. Kinematic data were collected every five minutes beginning at minute one. Initial contact angle (IC), maximum angle (MAX) during midstance, and latency (Tmax) between IC and MAX were calculated for the ankle and knee joints in the frontal and sagittal planes. No significant differences were observed between footwear. Rearfoot inversion ($F_{3,33}$ = 9.72, $p < .001$) and knee flexion ($F_{6,66}$ = 5.34, $p < .001$) at IC increased over time. No significant differences were detected for MAX over time. Tmax for dorsiflexion ($F_{6,66}$ = 10.26, $p < .001$), rearfoot eversion, ($F_{6,66}$ = 7.84, $p < .001$) and knee flexion ($F_{6,66}$ = 11.76, $p < .001$) increased over time. Maximum eversion during midstance is related to the angle at initial contact, and regardless of footwear type, IC and Tmax increased over the duration of the run. No differences in the ankle and knee sagittal or frontal plane kinematics between minimalist, habitual, and maximalist footwear were observed During a self-paced run.

KEY WORDS: Biomechanics, Lower Extremity, Joint timing, Footwear, Injury prevention

INTRODUCTION

Running is associated with high injury rates, along with its many physical benefits. Runners are suggested to change their shoes every 250-500 miles to avoid injury risks related to changes in running gait due to a potential 60% decrease in shock absorption capacity (10). Alterations in footwear may increase lower extremity injury risk (25). Footwear functions include shock absorption, forefoot force redistribution, and protection against the ground (25). However, barefoot/minimalist running proponents state that cushioned shoes potentially alter running gait and increase injury risks (5).

Effects of running shoes on the human body, especially the lower extremity musculoskeletal system, have been studied by many with the minimalist and maximalist at the polar opposite extreme. Minimalist shoes are said to have less cushioned midsoles (< 10mm), greater sole flexibility, and less motion control. Maximalist shoes are heavily cushioned with elevated heels, thick midsoles, arch supports, and motion control features. Minimalist footwear has been commonly investigated due to claims of reduced injury risk through specific kinematic changes, such as changes from heel-toe landing style to forefoot running (19, 21). Soares et al. (21) reported decreased knee flexion, suggesting reduced patellofemoral pain. In contrast, Willy and Davis (30) reported more dorsiflexion and knee flexion when running in cushioned minimalist shoes compared to neutral shoes.

Maximalist footwear is far less investigated. However, cushion differences between maximalist and minimalist shoes may alter joint angles primarily in the sagittal plane. Ankle motion may be a significant cause of running injuries (22) in which sagittal plane movement and vertical load influence coupling between rearfoot motion and other joints (22). Minimalist running shoes may have significantly greater plantar flexion and less knee flexion upon initial contact (IC) than maximalist shoes (19, 20). In addition, they may reduce impact forces between the runner's foot and the ground (4) because the runner adopts a more plantarflexed ankle, altering the location of force absorption due to a reduction in the shock absorption capacity at the knee upon landing (19, 21). These adaptations may reduce runner injury risk by reducing the center of mass vertical velocity and magnitude of impact (20). In contrast, since injury prevention tends to focus on the reduction of impact forces, the maximalist design of more cushioned midsoles has surfaced in hopes of reducing the impact between the foot and ankle at IC and potentially reduce injury.

Differences in footwear kinematics have been investigated across various prolonged running durations. Moore and Dixon (16) analyzed the differences across a 30-minute run during barefoot running and reported dorsiflexion and knee flexion increased at IC over time; however, there were no significant differences after 20 minutes suggesting stabilization (16). Kinematic changes throughout an exhaustive prolonged run regardless of footwear have been previously reported (6, 8, 26). These reports include increased knee flexion at IC and midstance (6), increased maximum eversion during midstance (6, 8, 26), and increased inversion at IC (6). It was suggested that an exhaustive run increases rearfoot motion (26). Willson et al. (29) investigated the effect of two weeks of training with minimalist footwear and reported increases in knee flexion at IC post-training (29). Another study assessing a 6-month follow up between minimalist and neutral footwear reported that runner's in a neutral shoe exhibited a greater knee abduction upon midstance (15). Regardless of footwear, during a training session, ankle dorsiflexion at IC and eversion at IC and midstance increased over time while knee flexion decreased (15). Few studies have assessed kinematic changes over one bout of prolonged running in relation to footwear. It is imperative to accurately analyze gait over time to provide physicians and the shoe industry with appropriate information concerning injury risk and optimal performance.

Reduction in impact force, influenced by the sagittal plane ankle and knee kinematics, is reported to reduce potential risks of overuse running injuries. However, overuse running injuries are commonly investigated through either rearfoot kinetic or kinematic variables (13). Rearfoot kinematics, including magnitude and rate of foot pronation, have been suggested to be contributing factors for overuse running injuries (13), indicating that the risk of injury increases if the foot lands in a vulnerable position. Landing in a vulnerable position at IC, where force applications are shorter in duration and less in amplitude (25), is likely to follow through to midstance where longer and greater forces are exhibited, increasing the risk of injury.

The most prevalent sites for overuse running injuries occur at the ankle and knee (2, 11). Current research primarily focuses on kinetics; however, the kinematic boundaries of the impact force are equally important. Novacheck (25) stated that IC forces have less amplitude and shorter durations, but active forces during the latter portion of stance are also threatening. This statement can also be applied to IC kinematics, indicating angles occurring within midstance with greater forces can be threatening. With this relationship between IC and midstance, IC kinematics might be a precursor for when the maximum joint angles occur during stance. If the body has poor proprioception and is unaware of the movement and positions of the lower extremity, improper loading at IC may be exhibited (12). Few researchers have assessed the influence of IC on the maximum joint angles during midstance. Furthermore, abnormal timing between two joints can lead to increases in injury (23). Small timing differences between maximum rearfoot eversion and maximum knee flexion have been reported in previous literature (7, 23). However, these differences are deemed to be a regular occurrence. Asynchronicity between joints presents a potential risk for injury (7, 8).

Literature comparing frontal and sagittal planes of motion at the beginning and end of a run miss the important moments during the middle of a run. To be more relevant to injury prevention and to properly understand how one progresses from the beginning to the end, the middle portion of the prolonged run, including the effects of footwear, is important to investigate. Therefore, the purpose of this study was to assess lower extremity kinematic changes and the relationship between kinematic parameters at IC and midstance with prolonged running under the influence of different types of footwear. We hypothesized that each joint angle and latency to maximum joint angle (Tmax) would be sensitive to shoe types and run duration. Many reports have focused on rearfoot motion in relation to injury prevention, but few have looked at the relationship between IC and maximum rearfoot angle. Therefore, the second hypothesis was that there would be a significant relationship between the rearfoot angle at IC and the maximum angle during midstance (MAX).

METHODS

Participants

Twelve healthy participants were recruited and informed about the testing procedures and possible risks. Participants were excluded from the study if they did not meet the following inclusion criteria: 1) 18 - 45 years of age; 2) Recreational runner (≥ 10 miles/week); 3) No existing lower extremity injuries at the time of testing; and 4) Answered no to all PAR-Q questions. The local ethics review committee approved the study. Participants signed the informed consent form before the starting of data collection.

An initial visit consisted of providing informed consent, a health screening, and collection of the required anthropometric data (i.e., age, sex, height, body mass, and running experience). Each participant completed three testing sessions with different running shoes for each session (participant's habitual running shoes; minimalist Nike Flex; and maximalist Hoka One One). Testing orders were counterbalanced and occurred 48 - 72 hours apart to reduce potential fatigue effects. Each participant ran at the same self-selected pace (from the first session) for 31 minutes for each testing session. Kinematic data were collected for 10-seconds at 5-minute intervals starting at the 1-minute mark. Marker trajectories were tracked at 120Hz using a 3-D motion capture system (Bonita 10 cameras; Nexus Version 2.3.0.88202; Vicon Motion Systems Ltd., Oxford, UK).

Protocol

For each session, seven retroreflective marker (14mm) cluster sets were placed on the participant prior to the warm-up utilizing a modified Helen Hayes model (28). Placement of clusters consisted of the lateral aspects of the thigh, leg, and rearfoot. Participants were instructed to perform a 10-minute walk/run warm-up in their habitual running shoes to accommodate to the tracking clusters as well as to reduce injury risk and muscle cramping throughout the session. Following the warm-up, 16 retroreflective anatomical markers were placed on the left and right iliac crests, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, and the first and fifth metatarsal heads (28). A 5-second standing static trial was recorded (Figure 1), and the anatomical markers were then removed. Participants were not instructed on how to run or land in different shoe conditions.

Data Analysis: Sagittal planes for the ankle and knee and frontal planes of the subtalar and knee joints were examined. Joint angles were quantified using a Cardan sequence of rotations (where X is flexion/extension; Y is ab-/adduction and Z is internal/external rotations or inversion/eversion for the subtalar joint). Ten consecutive stride's 3-D lower extremity joint kinematics were analyzed for every 10-seconds of data collected. 3-D marker coordinates were filtered with a 14 Hz low-pass, fourth-order zero-lag Butterworth filter. Visual 3D (Version: 6.00.27, C-Motion Inc., Germantown, MD) was used for kinematic data analysis.

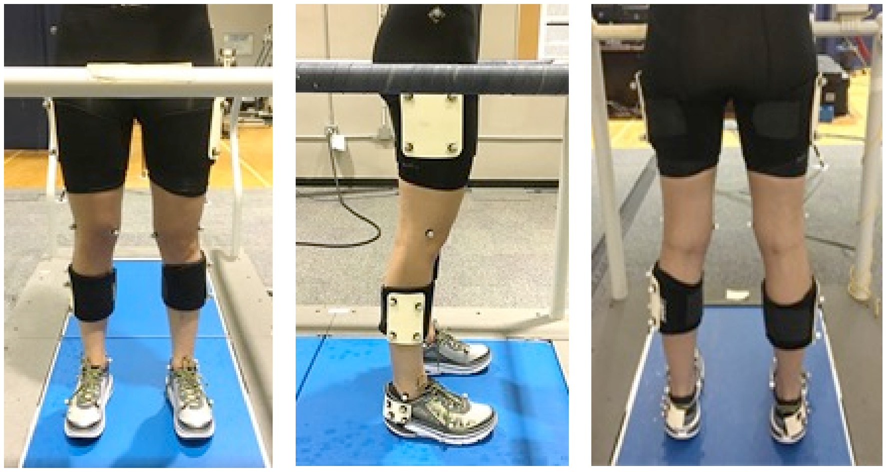

Figure 1. Retroreflective marker placement for each participant during the static trial. Following the static trial, the single anatomical markers were removed, and the cluster markers remained.

Stance began with a force greater than a 50N threshold. The first 40% of the gait cycle was analyzed as the stance period. The IC was defined when the stance began. MAX and Tmax were calculated in the sagittal and frontal planes.

Statistical Analysis
IC, MAX, and Tmax for knee and ankle joints in both sagittal and frontal planes were selected as outcome variables. All variables were assessed for normality. Each was examined using a separate 3 (shoes) x 7 (time points) ANOVA with repeated measures only when the sphericity assumption satisfied the Mauchly's sphericity test. Greenhouse-Geisser correction was applied if the sphericity assumption was violated. Statistical significance was set at .05 *a priori*. Pairwise comparisons with Bonferroni adjustments were used for post-hoc analysis following a significant main effect. Effect sizes (Cohen's d) were calculated for each significant comparison. Small effect was defined as $0 < d \leq .2$, medium effect as $.2 < d \leq .5$, and large effect $.5 < d$ (3). A Pearson Product correlation was used to assess the relationship between IC and MAX for the rearfoot. All statistical analyses were completed using SPSS/PASW (IBM Inc., v.25, Chicago, IL).

RESULTS

Twelve participants (6 male; 6 female) finished the three 31-minute data collection sessions without incident. Their age was 24.8 ± 8.4 (Mean ± Standard deviation) years old, height was 174.1 ± 9.7 cm, and body mass was 70.5 ± 9.3 kg. The participants had spent on average, 8.2 ± 5.8 months running in their habitual shoes by session one, with a weekly running distance of 26.4 ± 12.6 km and averaged 6.7 ± 2.4 years of running experience. The average shoe size tested was 9.5 ± 1.5. The average self-selected pace for the prolonged run tested was 2.9 ± 0.3 m/s. Exemplar outcome variables are presented in Figure 2A-D with knee and ankle angles in the sagittal and frontal planes during the first 40% of the gait cycle.

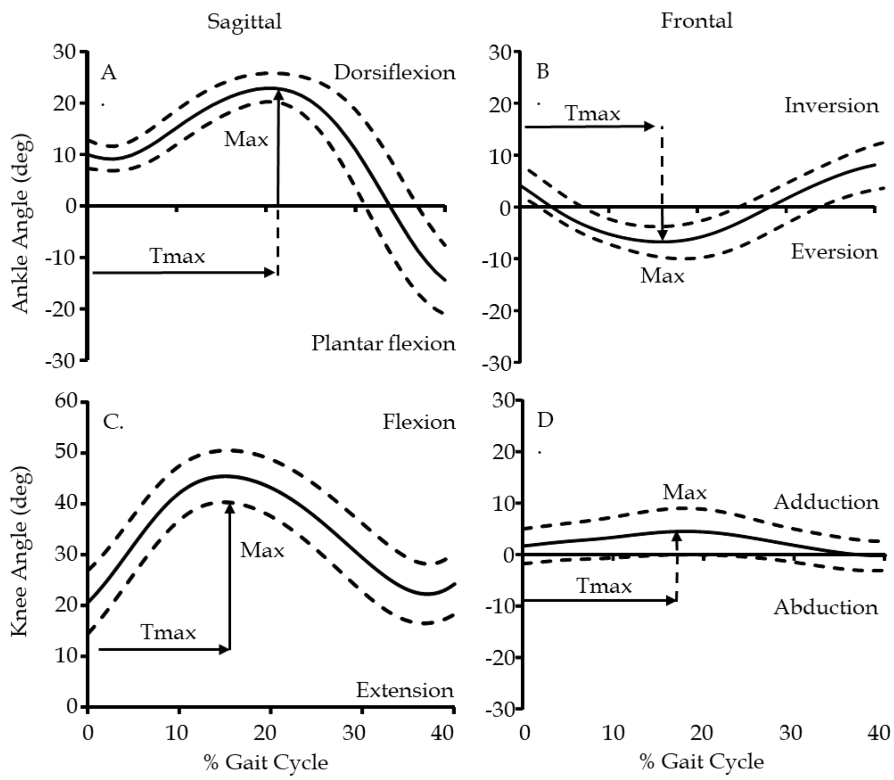

Figure 2A-D. Ensemble curves of the ankle (A, B) and knee (C, D) joint angles in the sagittal (A, C) and frontal (B, D) planes for the first 40% of the gait cycle (subsequent initial contacts defined as 100% gait cycle). The vertical arrows indicate maximum angles (Max) during midstance while the horizontal arrows indicate the relative times (Tmax) it took to get to the maximum angles during midstance. The dashed lines represent one standard deviation above and below the mean.

We failed to observe differences between shoes nor shoe-time interactions. Thus, only the influence of running time on the outcome variables will be presented.

Among all outcome variables, the sphericity assumption was violated by only the frontal plane ankle angle. A Greenhouse-Geisser correction was applied. Among all four IC, ankle angle in the frontal plane ($F_{3,33} = 9.72$, $p < .001$) and sagittal plane ($F_{6,66} = 5.95$, $p < .008$) and knee angle in the sagittal plane ($F_{6,66} = 5.34$, $p < .001$) changed with time significantly (Figure 3B & 3C). The significant ($p < .05$) pairwise comparison results are presented with effect sizes (d) in the corresponding figures. IC inversion at minute 5 was significantly less than that of the last 15 minutes (specific effect sizes reported in Figure 3). Moreover, IC inversion at minute 10 was significantly less than that last 10 minutes. Finally, IC inversion at minute 15 was significantly less than that of minute 30. Sagittal ankle IC was significantly increased from minute 0 to 10. Knee flexion IC at minute 0 was significantly less than that of minute 5 while that of minute 5 and 10 was significantly more than that of minute 25.

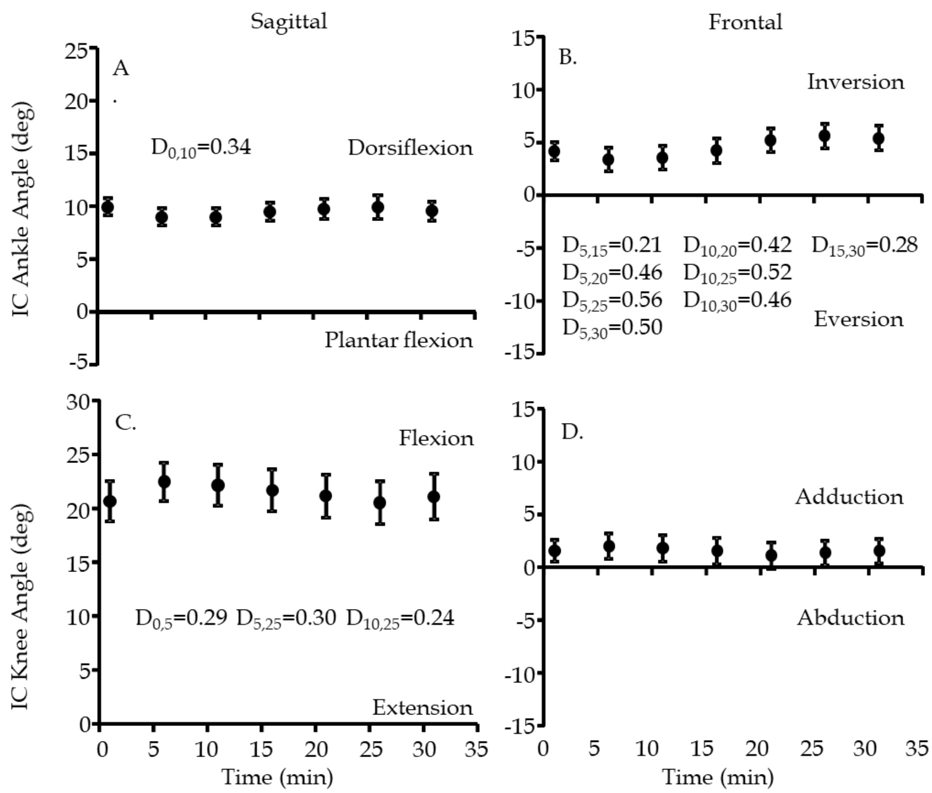

Figure 3A-D. Angles (mean and standard error of the mean) at initial contact for the ankle (A, B) and knee (C, D) joints in the sagittal (A, C) and frontal (B, D) planes across the 31-minute run. Greater than moderate effect sizes of pairwise comparisons were reported here only if the outcome variable exhibited significant changes with time (B, C).

We failed to detect an effect of running time on MAX knee and ankle angles in the frontal and sagittal planes during midstance. (Figure 4A-D).

There were significant differences observed for ankle Tmax in both dorsiflexion ($F_{6,66} = 10.26$, $p < .001$) and eversion ($F_{6,66} = 7.84$, $p < .001$) (Figure 5A, 5B) and only in knee flexion ($F_{6,66} = 11.76$, $p < .001$) (Figure 5D). Only greater than 0.2 effect size (d) is presented in Figure 5 for pairwise comparisons. Peak dorsiflexion/eversion (Figure 5A/5B) during stance occurred during the first 10 minutes compared to a later occurrence during the last 10 minutes. MAX knee flexion was related to running time in a nonlinear fashion (Figure 5C). MAX knee flexion during stance was reached significantly earlier at minutes 5 and 10 compared to minutes 0, 20, 25, and 30. Similarly, MAX knee flexion was reached earlier at minute 15 compared to minute 20.

Pearson Product correlations were examined after satisfactory normality tests. IC rearfoot angle was significantly ($R_p = .487$, $p < .0001$) correlated with MAX eversion during stance (Figure 6).

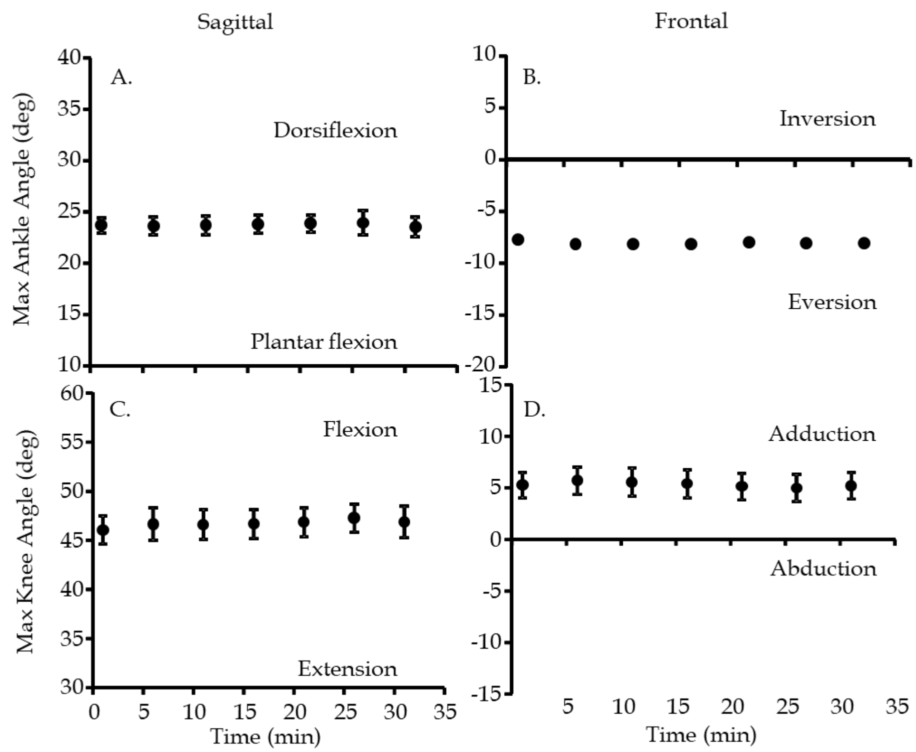

Figure 4A-D. Maximum (Max) (mean and standard error of the mean) angle during stance for the ankle (A, B) and knee (C, D) in the sagittal (A, C) and frontal (B, D) planes across the 31-minute run.

DISCUSSION

The purpose of this study was to assess knee and ankle kinematic changes with prolonged running under the influence of different types of footwear. The first hypothesis that angles and latencies are sensitive to shoes and run duration was partially supported. No significant footwear effects were observed on joint kinematics over prolonged running. However, running time affected rearfoot inversion and ankle/knee flexion at IC and Tmax. The results supported our second hypothesis with a significant correlation between rearfoot angles at IC and midstance.

We have observed increasing knee flexion at IC during the first five minutes, which then decreased towards the end at minute 25. These results are similar to previous literature (6, 16). We have also observed a lack of change in peak dorsiflexion at IC over time, which was previously reported (14), although contrary to some reports (16). Increased knee flexion, along with stable dorsiflexion, suggests that runners used their knee more rather than their ankle to attenuate impact and prevent potential injuries in the later part of the prolonged run (16).

IC inversion increased significantly from minute 5 to minutes 15-30 in agreement with previous work (6), although others have reported no change in rearfoot angle post-exhaustive run (8, 26). Derrick et al. (6) provided the rationale that inversion increases coupled with IC knee flexion increases may lead to a more efficient way to accelerate the effective mass forward during running, which could potentially attenuate impact forces and reduce injury risk.

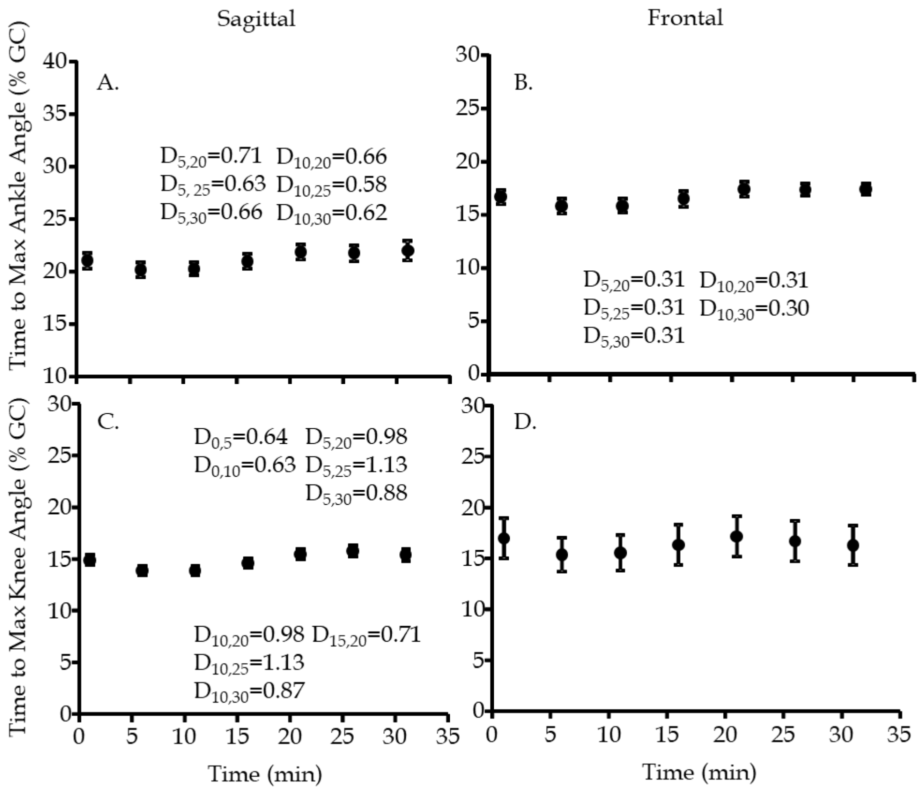

Figure 5A-D. The time it took to reach the maximum angles (Mean and standard error of the mean) during stance for the ankle (A, B) and knee (C, D) in the sagittal (A, C) and frontal (B, D) planes across the 31-minute run. Greater than moderate effect sizes of pairwise comparisons were reported here only if the outcome variable exhibited significant changes with time (A-C).

The lack of MAX changes observed differs from previous reports (8, 14), although our results were similar to the literature, with an average of approximately 8° (8, 18). The experience of the runners could explain the lack of change studied here, and not being in an exhaustive state that may lead to altered mechanics (14).

While most studies focus on joint angles alone, abnormal timing of two joints has also been suggested to influence injury risk (23). Smaller differences in timing between the two joints represent a more synchronous relationship (9). Knee flexion and rearfoot motion are thought to occur at approximately the same time during midstance (23). Here, Tmax for ankle sagittal and frontal planes and knee sagittal plane motion was significantly different over time. The results from this study indicated increased latencies for eversion and knee flexion during midstance at the end of the run for minutes 20 - 30 compared to the beginning of the run at minutes 5 and 10. Knee flexion Tmax ranged from 13.9 - 15.8% of the gait cycle while eversion and dorsiflexion MAX ranged from 15.8 - 17.4% and 20.1 - 21.9%, respectively. Since eversion is relatively synchronous with knee flexion and occurs before plantar/dorsiflexion, controlling MAX eversion could potentially reduce ankle and knee injury rates.

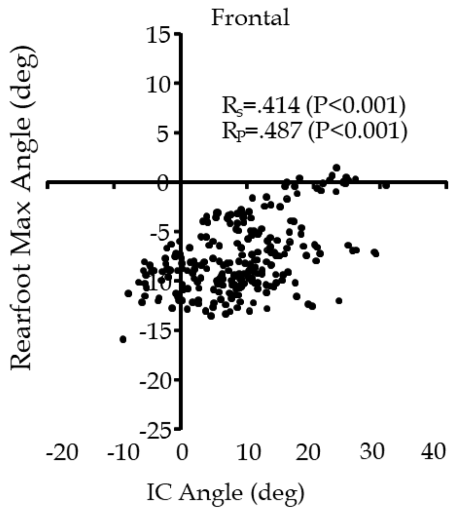

Figure 6. Parametric (R_p) correlation coefficients are presented here, where the horizontal axis represents the angle at initial contact (IC), and the vertical axis represents the Maximum angle during stance for the rearfoot.

Delayed eversion may disrupt normal joint coupling and contribute to overuse running injuries (8, 24). MAX occurred in the following order knee flexion, rearfoot eversion, and then ankle dorsiflexion. Dierks and Davis (7) observed similar results in which maximum knee flexion during midstance occurred prior to maximum eversion. The relatively small timing differences between peak knee flexion and maximum eversion coincide with previous literature (7, 23). Few studies have assessed latency changes with prolonged running. Dierks and colleagues (8) reported no difference in latency between the beginning and end of an exhaustive run. However, joint motion order was similar to the results from this study with MAX knee flexion occurring first and relatively synchronous with MAX eversion. Although eversion and knee flexion Tmax increased overtime for this study, these alterations occurred simultaneously. If delayed eversion occurs apart from delayed knee flexion, the risk of injury may increase.

IC and MAX have both been suggested to contribute to injury rates, yet the relationship between the two angles has not been thoroughly assessed. The significant correlation between the two angles suggests that MAX eversion experienced during midstance was influenced by less inversion at IC regardless of shoe designs incorporating rearfoot motion control or stability (25).

There are a few limitations. We did not record perceived exertion nor heart rate, so we don't know if participants reached fatigue or have been exhausted. However, our recreational and experienced participants were running for 30 minutes at a self-selected pace. The same self-selected pace was used for all testing sessions for a given participant. No participant complained about fatigue at the end of the testing sessions. Secondly, all participants in this study were rearfoot strikers; thus, our observations could not be generalized to other foot strike patterns. Future studies should investigate the effect of different footwear and prolonged treadmill running for midfoot and forefoot strikers. Finally, the interpretation and discussion of our observations could not be extrapolated beyond our 30-minute testing period.

In conclusion, initial contact angles and time to maximum angles were affected by running duration. Maximum eversion experienced during midstance was related to the rearfoot angle at initial contact regardless of footwear type. Most importantly, there were no differences in ankle and knee sagittal or frontal plane kinematics between minimalist, habitual, and maximalist footwear during a 30-minute run.

The authors have no conflicts of interest to report. This study was not supported by external funding. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. This research was carried out fully in accordance with the ethical standards of the International Journal of Exercise Science (17).

REFERENCES

1. Agresta C, Brown A. Gait retraining for injured and healthy runners using augmented feedback: A systematic literature review. J Orthop Sports Phys Ther 45(8): 576-584, 2015.

2. Braunstein B, Arampatzis A, Eysel P, Brüggemann G-P. Footwear affects the gearing at the ankle and knee joints during running. J Biomech 43(11): 2120-2125, 2010.

3. Cohen J. Statistical power analysis for the behavioral sciences. Routledge; 2013.

4. Cohler MH, Casey E. A survey of runners' attitudes toward and experiences with minimally shod running. PM R 7(8): 831-835, 2015.

5. Davis IS, Rice HM, Wearing SC. Why forefoot striking in minimal shoes might positively change the course of running injuries. J Sport Health Sci 6(2): 154-161, 2017.

6. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. Med Sci Sports Exerc 34(6): 998-1002, 2002.

7. Dierks TA, Davis I. Discrete and continuous joint coupling relationships in uninjured recreational runners. Clin Biomech 22(5): 581-591, 2007.

8. Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. J Biomech 43(15): 2993-2998, 2010.

9. Dierks TA, Manal KT, Hamill J, Davis I. Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. Med Sci Sports Exerc 43(4): 693-700, 2011.

10. Even-Tzur N, Weisz E, Hirsch-Falk Y, Gefen A. Role of eva viscoelastic properties in the protective performance of a sport shoe: Computational studies. Biomed Mater Eng 16(5): 289-299, 2006.

11. Hamill J, van Emmerik RE, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. Clin Biomech 14(5): 297-308, 1999.

12. Hesar NGZ, Van Ginckel A, Cools A, Peersman W, Roosen P, De Clercq D, et al. A prospective study on gait-related intrinsic risk factors for lower leg overuse injuries. Br J Sports Med 43(13): 1057-1061, 2009.

13. Hreljac A. Impact and overuse injuries in runners. Med Sci sports Exerc 36(5): 845-849, 2004.

14. Koblbauer IF, van Schooten KS, Verhagen EA, van Dieën JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. J Sci Med Sport 17(4): 419-424, 2014.

15. Malisoux L, Gette P, Chambon N, Urhausen A, Theisen D. Adaptation of running pattern to the drop of standard cushioned shoes: A randomised controlled trial with a 6-month follow-up. J Sci Med Sport 20(8): 734-739, 2017.

16. Moore IS, Dixon SJ. Changes in sagittal plane kinematics with treadmill familiarization to barefoot running. J Appl Biomech 30(5): 626-631, 2014.

17. Navalta JW, Stone WJ, Lyons S. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1, 2019.

18. Nicola TL, Jewison DJ. The anatomy and biomechanics of running. Clin Sports Med 31(2): 187-201, 2012.

19. Sinclair J, Fau-Goodwin J, Richards J, Shore H. The influence of minimalist and maximalist footwear on the kinetics and kinematics of running. Footwear Sci 8(1): 33-39, 2016.

20. Sinclair J, Richards J, Selfe J, Fau-Goodwin J, Shore H. The influence of minimalist and maximalist footwear on patellofemoral kinetics during running. J Appl Biomech 32(4): 359-364, 2016.

21. Soares TSA, Oliveira CFd, Pizzuto F, Manuel Garganta R, Vila-Boas JP, Paiva MCdA. Acute kinematics changes in marathon runners using different footwear. J Sports Sci 36(7): 766-770, 2018.

22. Stacoff A, Nigg BM, Reinschmidt C, van den Bogert AJ, Lundberg A. Tibiocalcaneal kinematics of barefoot versus shod running. J Biomech 33(11): 1387-1395, 2000.

23. Stergiou N, Bates BT, James SL. Asynchrony between subtalar and knee joint function during running. Med Sci Sports Exerc 1999.

24. Tiberio D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: A theoretical model. J Orthop Sports Phys Ther 9(4): 160-165, 1987.

25. Tom N, Novacheck T. Review paper: The biomechanics of running. Gait Posture 7(1): 77-95, 1998.

26. Van Gheluwe B, Madsen C. Frontal rearfoot kinematics in running prior to volitional exhaustion. J Appl Biomech 13(1): 66-75, 1997.

27. Warne J, Kilduff S, Gregan B, Nevill A, Moran K, Warrington G. A 4-week instructed minimalist running transition and gait-retraining changes plantar pressure and force. Scand J Med Sci Sports 24(6): 964-973, 2014.

28. Weinhandl JT, Joshi M, O'Connor KM. Gender comparisons between unilateral and bilateral landings. J Appl Biomech 26(4): 444-453, 2010.

29. Willson JD, Bjorhus JS, Williams III DB, Butler RJ, Porcari JP, Kernozek TW. Short-term changes in running mechanics and foot strike pattern after introduction to minimalistic footwear. PM R 6(1): 34-43, 2014.

30. Willy RW, Davis IS. Kinematic and kinetic comparison of running in standard and minimalist shoes. Med Sci Sports Exerc 46(2): 318-323, 2014.

31. Willy RW, Scholz JP, Davis IS. Mirror gait retraining for the treatment of patellofemoral pain in female runners. Clin Biomech 27(10): 1045-1051, 2012.