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Stance Quantified in Real World Scenario: Changes in Knee Joint Kinematic between Shod and Barefoot Running

Gurtej Singh Grewal[1]*, Mary Lou Bareither[2], Matthew Walthers[3], Jacqueline Lee-Eng[1], Ruben Goebel[4] and Bijan Najafi[1]

[1]*Interdisciplinary Consortium on Advanced Motion Performance (iCAMP), University of Arizona, College of Medicine, Tucson, Arizona, USA*

[2]*Department of Kinesiology and Nutrition, University of Illinois at Chicago, Chicago, IL, USA*

[3]*Department of Physical Therapy, University of Illinois at Chicago, Chicago, IL, USA*

[4]*Sport Science Program, Qatar University, Doha, Qatar*

***Corresponding author:** Dr. Gurtej Singh Grewal PhD, Interdisciplinary Consortium on Advanced Motion Performance (iCAMP), University of Arizona, College of Medicine, 1656 E Mabel Street, Tucson, AZ 85724, USA, Tel: 520333 7920; E-mail: ggrewal@surgery.arizona.edu

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Abstract

Background: Barefoot running has been reported to cause favorable biomechanical changes during running. However, knee joint kinematic changes in stance phase during different running conditions in an out-of-laboratory setup has not been explored. The aim of this study was to evaluate three dimensional changes in knee kinematics among habitual shod runners outside of gait laboratory during shod and barefoot running.

Methods: Using unobtrusive body-worn sensors mounted to anatomical segments, kinematic data were acquired in twelve healthy young individuals (Age 22.5 ± 2.2 years, BMI 21.4 ± 2.0 Kg/m^2). Several kinematic parameters were compared between shod and barefoot running including three dimensional knee joint range of motion, tibia internal-external rotation, knee medial-lateral impact, stride time, flight time, contact time and shock propagation time.

Results: With no significant difference (p=0.21) in running speed between the two running conditions, significant reduction (6.4%, p=0.005) in flexion-extension range and increase (8.4%, p=0.0001) in internal-external rotation range of knee joint was observed during barefoot running compared to shod. The knee joint Varus-valgus range of motion and impact was not influenced by running condition. Barefoot running also caused a significant increase of tibia rotation (p=0.001), shock transmission time from tibia to sacrum (p=0.009) along with decrease in stride time and flight time (p=0.0001) compared to shod running.

Conclusion: The current study explored three dimensional changes in knee joint kinematics during stance phase under different running conditions in an out-of-laboratory environment. The results suggest that habitual shod runners transitioning to barefoot running can have negative impact from significant increase in range of internal-external rotation of knee joint and tibia from barefoot running. Future research studies are warranted in a larger sample size to confirm the findings.

Keywords: Barefoot running; Shod running; Knee kinematics; Impact acceleration; Body-worn sensors

Introduction

Running is one of today's most common recreational activities. Although several technical advancements in modern footwear have occurred, however due to multifactorial nature of cause for injuries the incidence of running related injuries is still high. Running related injuries based on 17 studies have been reported to vary between 19% to 79% per year depending upon location, type of injury and population [1,2], with most common reported site of injury as knee joint [2-5]. A common injury of knee joint both during walking and running is ligament injury related to increased tibial and knee joint internal external rotation [5,6]. And now with recent increase in trend of running barefoot as it is thought to have favorable biomechanical changes from reduced impact peak that may reduce running related injuries [7,8]; it becomes vital to compare 3-dimensional knee joint kinematics. A recent survey reported that traditional shod runners experience more lower extremity related injuries than runners with minimalist shoes, however no significant findings were reported for comparison between barefoot and shod runners besides preference to anterior foot strike among barefoot runners [9]. Several spatio-temporal and kinetic changes have been associated with barefoot running [8,10-12]. A number of studies also claim favorable changes in biomechanical and physiological parameters including reduction in impact load, joint moment, energy cost and better plantar sensation during barefoot and minimally shod running [13-16]. Early studies have also associated adaptations during static barefoot weight bearing conditions including deflection of the medial longitudinal arch which may contribute towards reduced injuries during barefoot running [17]. Contrary findings have also been published with no significant difference in impact force measured [18] or lack of information was available relating injury trend to style of running [19]. Based on reduction in knee joint impact the review also reported that barefoot running may possibly reduce knee joint load and injuries [19]. Since knee joint injuries are prevalent in many sports related activities, it is imperative to explore knee joint kinematics in out of laboratory setup during different footwear conditions.

The biomechanical changes between shod and barefoot running also affect knee joint angular range of motion (ROM), as reported by changes in knee flexion-extension range [18]. Therefore, the changes in knee joint biomechanical parameters happening out of laboratory running including joint flexion-extension; internal-external rotation and Varus-valgus range of motion should be explored. Most running related studies have focused on measuring either ground reaction forces or joint torques and kinematics which of course are vital to understand the mechanism and impact loading experienced by joints. However, with the exception of a few studies [11,15], most have been limited to the sagittal plane [13,14] measurements of range of motion and impact loading. Further, the measurement protocols have been either limited to fewer steps in a laboratory setup [18] or running trials on an instrumented treadmill [14,15] which may not reflect the actual running environment for many runners or soccer athletes performing unanticipated cutting maneuvers. Our research results may have a significance for habitual shod runners who wish to transition into barefoot running. Further, assessment of knee instability during different running conditions can significantly contribute towards appropriate interventions for reducing ACL related injuries. The aim of the current study was to explore three dimensional stance phase kinematic changes associated with knee joint during shod and barefoot running in an ecological setting.

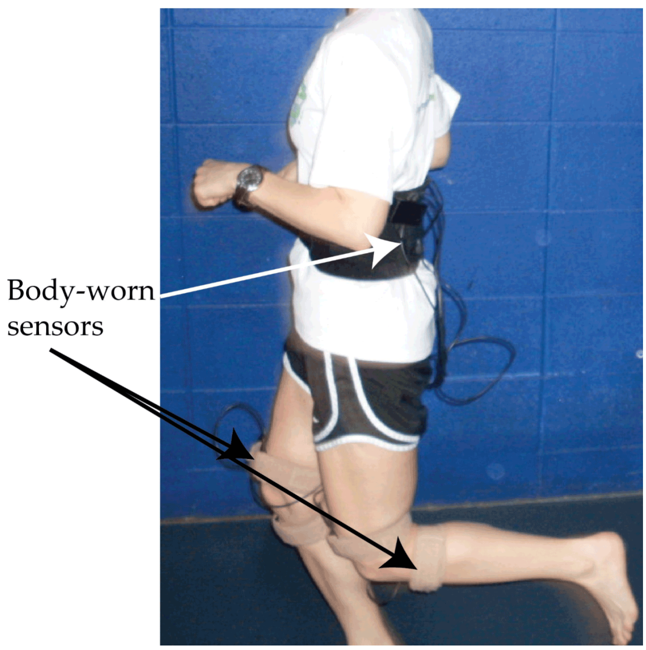

Figure 1: An illustration of body-worn sensor mounting during the two running trials.

Methods

Subjects and experimental protocol

The current study recruited 12 (6 male, 6 female) healthy young individuals from the University of Illinois, Chicago with no or minimum barefoot running experience. Exclusion criteria included a medical condition, pregnancy or any lower extremity injury that risked their safety or limited their ability to run habitually. Each participant signed an informed consent form approved by the Institutional Review Board of the University of Illinois at Chicago. Prior to running, participants' anthropometric data including age, gender, ethnicity, height and weight were recorded. Participants were instructed to run at a comfortable self-selected pace in shod followed by barefoot condition for a distance of 800 feet with recovery time of 10 minutes between the two trials. Warm up trials were given for acclimatization. The data were collected in an indoor gymnasium at the University of Illinois at Chicago on hard floor.

Equipment

In order to have maximum comfort during running, participants wore their personal training shoes; this also prevented atypical running patterns. All participants wore shoes with similar characteristics (tennis or running shoes). Kinematic data were collected using validated body-worn sensors (LegSysTM BioSensics, LLC, MA, USA) securely mounted on different body segments using elastic Velcro bands, (Figure 1). The system has been widely used for assessment of gait and measurement of three dimensional joint angles [20-23]. Two sensors were mounted on each leg; one at the site of the tibial tuberosity [24,25], and the other just proximal to the patella. An additional sensor was attached to the lower back, near the lumbo-sacrum junction. Each sensor incorporated a tri-axial accelerometer, gyroscope and magnetometer. Data were transferred wirelessly over ad-hoc WiFi network at frequency of 100 Hz. Besides raw data from inertial sensors, a fusion algorithm provided orientation information as quaternion for further estimation of angles [26].

Assessment of parameters

For comparison between the two running conditions we quantified changes in tibia internal-external rotation range, knee joint flexion-extension range, Varus-valgus range and internal-external rotation range. Additionally, we measured knee medial-lateral impact (g), impact at sacrum (g), running temporal parameters including cycle time, flight time, contact time and impact propagation time from tibia to sacrum. Data collected from body-worn sensors was analyzed offline in MatLab R2012b (Massachusetts: The MathWorks Inc). Instances of initial contact (IC) and terminal contact (TC) were obtained from the angular velocity plots of the tibia mounted sensors around the medial-lateral axis of the sensor [20]. The instances of IC and TC have distinctive signal features including sharp negative peak from changes in pivot of rotation from hip to ankle joint during IC and back to hip during TC. Using validated technique and algorithms previously described in literature these instances were identified [20]. Figure 2A illustrates identification of IC and TC for estimation of stride time, contact time and flight time.

Based on the detected instances, stride time, contact time and flight time was estimated for each leg. Maximum mid-swing angular velocity for each shank was obtained from peak detection of gyroscope data. Vertical acceleration of sacrum mounted sensor was recorded at the instance of IC to quantify acceleration impact and similarly for tibia mounted sensor for quantifying knee medial-lateral impact using local peak detection algorithm [20].

$$\text{Stride time} = (ICi+1 - ICi) \quad (1)$$

$$\text{Contact time} = (TCi - ICi) \quad (2)$$

Flight time (ICi+1 – TCi) (3)

Where, i is index of step.

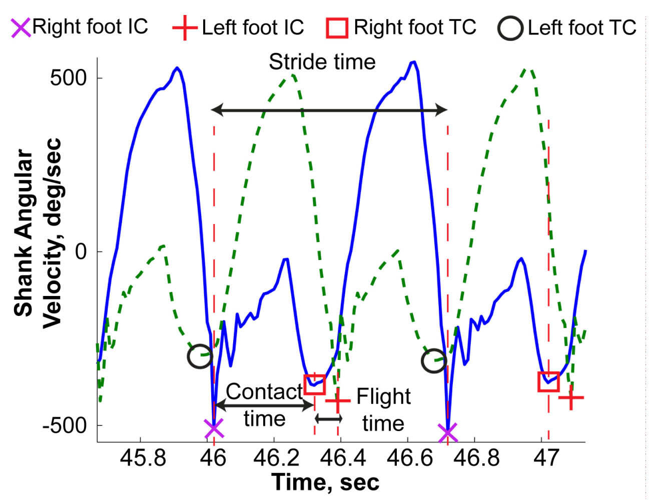

Figure 2: (A) Shank derived gyroscope data illustrating stride time, contact time and flight time.

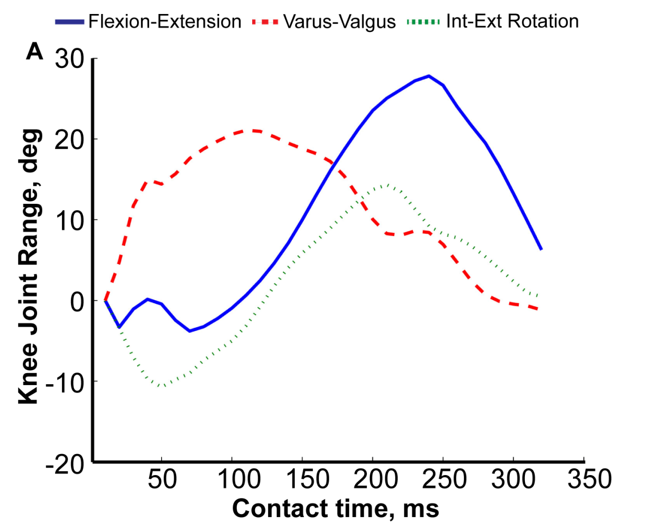

Figure 2: (B) Three dimensional estimation of knee joint angle from integration of gyroscope difference of thigh and shank mounted sensors during contact time (stance).

The shock propagation time from tibia to sacrum was estimated based on time difference between tibia received vertical acceleration impact and sacrum received vertical impact at IC. The acceleration was corrected using quaternion approach [27]. Further, the ROM of tibia segment and knee joint during stance phase was obtained by widely implemented integration technique [28]. During knee joint range estimation the integration was performed on difference of gyroscope signals from thigh and tibia mounted sensors in all the three axis [21,29], (Figure 2B). The average running speed was calculated based on the total distance (800f) and the time taken.

Statistical analysis

Statistical analysis was completed in SPSS® version 21 (SPSS, Inc. Chicago, IL, USA). The measured kinematic parameters between two footwear conditions were compared using repeated measures ANOVA followed by post hoc LSD pairwise comparison. Independent variables of age, BMI and gender were used as covariates during analysis. The p value of less than 0.05 was considered statistically significant. Effect sizes were calculated as Cohen's d with value of 0.2 considered small, 0.5 medium and 0.8 as large [30]. The parametric values were averaged between participants and the outcomes were compared between shod and barefoot running condition. The results have been expressed as mean ± SD with 95% confidence interval in tables and mean ± SE in bar graphs.

Results

Kinematic variables

No significant difference was observed for running speeds between the two running conditions (p=0.214) with values of 2.29 ± 0.52 m/s and 2.14 ± 0.15 m/s for shod and barefoot condition respectively. Knee flexion-extension reduced significantly during barefoot running with values of 33.29 ± 4.6 deg for shod and 31.16 ± 3.7 deg (p=0.005, 6.4%) during barefoot running with effect size of d=0.49 (Figure 3A). A significant increase was also observed for internal-external knee rotation from barefoot running with values of 18.77 ± 5.3 deg and 20.35 ± 5.0 deg (p=0.0001, 8.4%, d=0.31) for shod and barefoot condition respectively, (Figure 3A). No changes were observed for Varus-valgus motion range during the two running conditions (p=0.882, d=0.04) with average values of 17.73 ± 2.59 deg for shod and 17.84 ± 2.62 deg for barefoot running. Similar changes were observed for Tibia with internal-external rotation range values of 14.47 ± 3.9 deg and 17.62 ± 4.6 deg (p=0.001, 21.7%, d=0.71) for shod and barefoot condition respectively. During barefoot running the angular velocity of the tibia segment in the sagittal plane was increased by 7.7% (p=0.0001, d=0.80); the value increased from 518 ± 46 deg/s in shod to 558 ± 52 deg/s during barefoot running, (Figure 3B). While age and BMI did not have any significant effect on measured parameters, gender had significant influence on knee internal external rotation range (p=0.019).

Impact and temporal characteristics

During barefoot running the medial lateral impact at knee joint was not significantly affected (p=0.820) with values of 2.11 ± 0.18 g and 2.10 ± 0.13 g during shod and barefoot condition respectively. Comparing the temporal parameters of stride time and flight time, a significant reduction in both was observed during barefoot running compared to shod (Figure 4A). The values dropped from 0.734 ± 0.03 s to 0.705 ± 0.02 s (p=0.0001, 3.9%, d=0.80) and 0.408 ± 0.02 s to 0.385 ± 0.02 s (p=0.0001, 5.6%, d=1.15) for stride time and flight time for shod and barefoot running respectively. The contact time however did not show any significant changes between the two running conditions (0.325 ± 0.01 s for shod and 0.319 ± 0.01 s for barefoot, p=0.172). The vertical impact shock transmission time from tibia to sacrum was significantly increased (31.34 ± 5.7 ms Shod to 37.92 ± 7.6 ms Barefoot; p=0.009, 21%, d=0.95) during barefoot running (Figure 4B).

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Discussion

Impact and kinematic characteristics during shod and barefoot running have been the focus of continued research for years. With the advent of new footwear, several studies have examined the effect of footwear on foot loading, pressure, joint moment, joint stiffness and various other parameters. To our knowledge, the current study is the first to explore three dimensional knee kinematic changes during shod and barefoot running in an out of laboratory setup using body-worn sensors. Habitual shod runners were recruited with little or no barefoot running experience, using state-of-the-art inertial sensors several temporal and kinematic parameters were estimated and compared between the two running conditions.

Parameter	Shod	Barefoot	Effect size	Paired Differences			P value
				Mean Diff	95% CI of Diff		
	Mean±SD				Lower	Upper	
Knee Flexion-Extension, deg	33.28 ± 4.6	31.15 ± 3.8	1.07	2.13	0.83	3.43	0.005
Knee, Varus-valgus, deg	17.73 ± 2.6	17.83 ± 2.6	0.04	-0.11	-1.73	1.51	0.882
Knee Internal-External rotation, deg	18.77 ± 5.3	20.34 ± 5.0	1.49	-1.58	-2.02	-1.13	0.000
Tibial Internal-External rotation, deg	14.47 ± 3.9	17.62 ± 4.7	1.38	-3.14	-4.46	-1.82	0.001
Average Running Velocity, m/sec	2.29 ± 0.53	2.14 ± 0.15	0.36	0.15	-0.11	0.40	0.214
Shock propagation time, ms	31.3 ± 5.8	37.9 ± 7.7	0.94	-6.58	-11.01	-2.14	0.009
Contact time, ms	324.8 ± 17.6	319.5 ± 15.4	0.36	5.32	-2.86	13.50	0.172
Stride time, ms	732.9 ± 34.3	704.8 ± 28.9	1.94	28.12	17.33	38.95	0.000
Flight time, ms	408.1± 23.6	385.3 ± 24.7	1.91	22.82	14.45	31.18	0.000
Tibia Mid-swing Angular velocity, deg/sec	518.3 ± 46.3	558.1 ± 52.1	1.67	-39.7	-55.69	-23.74	0.000
Knee Medial-lateral shock, g	2.11± 0.2	2.10 ± 0.1	0.04	0.01	-0.12	0.15	0.820

Table 1: Changes measured in kinematic parameters during shod and barefoot running trial.

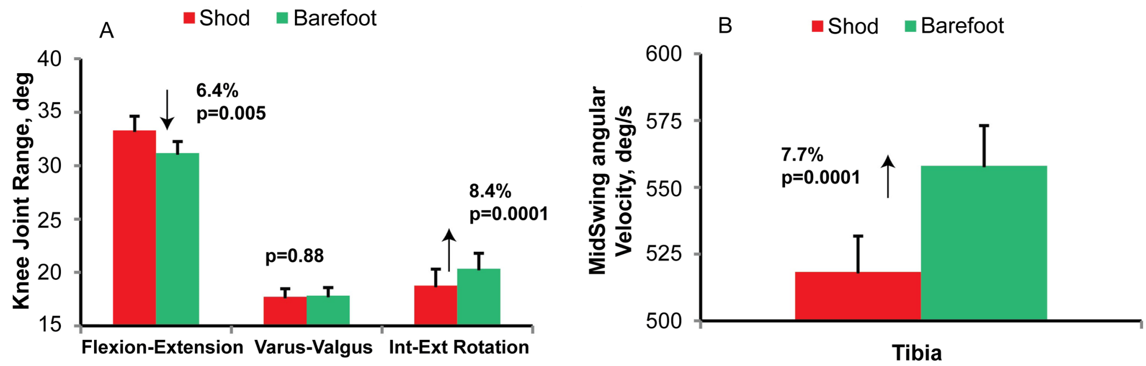

Figure 3: (A) Comparison of Knee range of motion and (B) tibia mid-swing angular velocity during shod and barefoot running trial conditions (Mean ± SE).

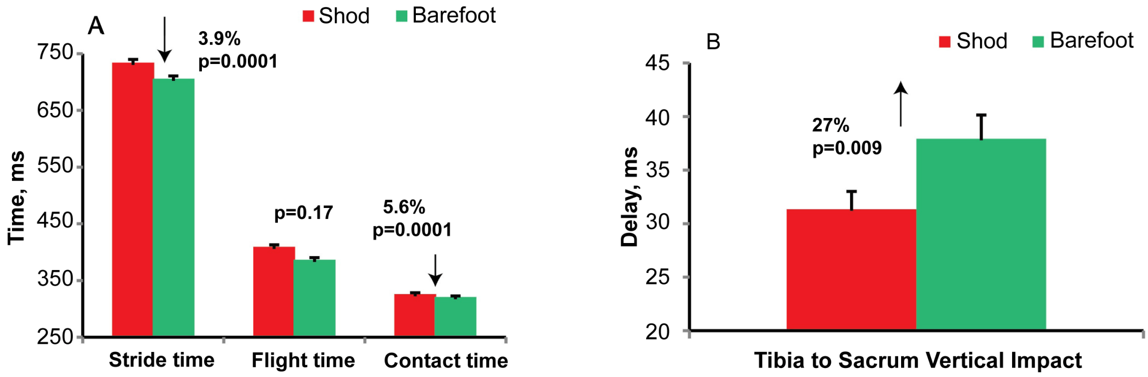

Figure 4: Comparison of temporal parameters between the two running conditions; (A) Stride time, Contact time and Flight time, (B) Shock transmission time from Tibia to Sacrum (Mean ± SE).

Our results report significant changes in knee joint range of motion during stance from barefoot running in particular, reduction in flexion-extension and an increase in knee internal-external rotation range compared to shod running. Reductions in knee flexion-extension range during barefoot running can also be derived from previously published literature [14,18,31,32]. Such reductions in knee flexion-extension range can be detrimental as found in research studies reporting increased risk of anterior cruciate ligament disruption from lower knee joint flexion-extension that increases anterior shear force applied on tibia from the quadriceps muscles [6,33].

The increase in internal-external rotation range of knee joint motion from barefoot running also demonstrates an unstable knee, which would need careful consideration from individuals making transition from shod to barefoot running. The increase in knee joint internal-external rotation is also partly contributed by the observed increase in rotation of the tibia which has been reported previously [31]. The increase in tibia and knee internal-external rotation demands caution during transition to barefoot running as increase in tibial/knee rotation has implications for running injuries [34]. It has been reported that increased knee internal rotation is detrimental to its stability and is one of the strong predictors for injuries like Iliotibial band syndrome [35]. In several cadaver studies it has been found that at certain knee flexion-extension angles the knee joint internal-external rotation is associated to the amount of ACL, specifically, reduction in ACL is associated to increased range of rotation in knee joint [36-38]. Therefore, it is speculative that increased internal-external rotation of knee joint from barefoot running may also have negative impact on ACL. Furthermore, a significant correlation between impact forces and tibia/knee kinematics has also been demonstrated in simulated ski-landing studies [39]. Studies have reported that ligament injury can be associated to increased internal-external rotation of both knee and tibia causing an instability in the knee joint prone to injury [40,41]. Interestingly in the current study we did not find any significant differences in knee Varus-valgus range or medial-lateral impact during the two running conditions. Literature has reported increased risk of injury from increase in knee Varus-valgus angles [35,42] especially in female athletes.

The current study also found changes in temporal parameters consistent with previous studies [14,15,18]. The stride time and flight time during barefoot condition were significantly reduced, which are associated with the touchdown pattern during barefoot running. A study demonstrated that the probability of tibial stress fractures can be reduced with reduction in stride length [43], therefore, the observed reductions in temporal parameters suggests that runners making the transition from shod to barefoot may reduce the probability of tibial stress fractures. However, a prospective study with a larger group of subjects is warranted to make such claims.

We also found changes in shock transmission time from the tibia to the sacrum between the two running conditions. During barefoot running trials shock propagation was significantly delayed. These findings are in line with the active mechanisms of shock attenuation where during forefoot strike an eccentric contraction of calf muscles increase the time of shock propagation resulting in shock attenuation [44]. It is worth mentioning here that results of any study comparing barefoot and shod running conditions may significantly vary depending on the methodology and participants of the study. For instance comparing habitual shod runners for shod vs. barefoot comparison may give different results than habitual barefoot runners for shod vs. barefoot comparison. An experienced barefoot runner may continue their running style during shod and vice versa, which may affect the outcome variables, as suggested by Squadrone and Gallozzi for noticed non-significant changes in energy cost during comparison [14].

Based on the literature findings on different running styles, it does seems that barefoot runners may benefit from reduced vertical impact forces, however the increased tibia and knee joint internal external rotation may increase injury risk. It may be beneficial to adapt to minimalist shoes as they have demonstrated changes in lower limb kinematics similar to barefoot running [13,14].

The current study has some limitations; it should be noted that since most of our participants did not have much history of barefoot running and did not wear exactly same footwear (type and brand) which may influence results, further it is not clear whether experienced barefoot runners would experience similar kinematic changes as found in this study. Second, we did not compare ankle joint kinematic which would contribute significantly to the underlying mechanism for biomechanical changes. Third, the order of trials was not randomized, which may have some influence on results. Finally, the foot touchdown technique (forefoot, midfoot or rearfoot) was not recorded during shod or barefoot to running in order to correlate to the changes in kinematic parameters. However, the findings do contribute to the knowledge in the field and highlight the possible risk of increased internal-external knee joint range of motion as a result of barefoot running. Further the implementation of body-worn sensors warrant future studies to perform out of laboratory measurements.

Conclusion

The current study explored changes in three dimensional knee joint kinematics during stance phase between shod and barefoot running among habitual shod runners. We implemented body-worn sensors to acquire out of laboratory running data over several hundred steps. We found that during barefoot running there are significant changes in tibia and knee joint range of motion especially increase in internal-external rotation range which could increase risk of injury. For generalization of the findings it is warranted to conduct out of laboratory future studies with larger sample size.

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