Title

The preferred movement path paradigm: Influence of running shoes on joint movement

Authors

Benno M. Nigg[1], Jordyn Vienneau[1], Aimée C. Smith[1], Matthieu B. Trudeau[1] , Maurice Mohr [1] and Sandro R. Nigg[1]

[1]Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada

Author Correspondence

Corresponding Author: Benno M. Nigg

Address: Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4
Phone: 403-249-1424
Email: nigg@ucalgary.ca

Abstract Purpose: (a) to quantify differences in lower extremity joint kinematics for groups of runners subjected to different running footwear conditions, and (b) to quantify differences in lower extremity joint kinematics on an individual basis for runners subjected to different running footwear conditions. **Methods:** Three-dimensional ankle and knee joint kinematics were collected for 35 heel-toe runners when wearing three different running shoes and when running barefoot. Absolute mean differences in ankle and knee joint kinematics were computed between running shoe conditions. The percentage of individual runners who displayed differences below a 2°, 3° and 5° threshold were also calculated. **Results:** The results indicate that the mean kinematics of the ankle and knee joints were similar between running shoe conditions. Aside from ankle dorsi-flexion and knee flexion, the percentage of runners maintaining their movement path between running shoes (i.e. less than 3°) was in the order of magnitude of about 80 to 100%. Many runners showed ankle and knee joint kinematics that differed between a conventional running shoe and barefoot by more than 3°, especially for ankle dorsiflexion and knee flexion **Conclusion:** Many runners stay in the same movement path (the preferred movement path) when running in various different footwear conditions. The percentage of runners maintaining their preferred movement path depends on the magnitude of the change introduced by the footwear condition.

Keywords: kinematics, running, injury, footwear

Introduction

Of the millions of people worldwide who run or jog, a substantial percentage (37% to 50%) experience running related injuries (4, 12, 25). Previous injuries, excessive mileage, and aberrant running mechanics, including excessive impact forces and rearfoot pronation have been associated with the development of those injuries (5, 8, 14, 18, 25). Running shoes with specific design features, such as, increased cushioning, stability and/or control have been constructed to help alleviate the development of running injuries previously linked to risk factors such as high impact forces or excessive pronation (13). Despite the implementation of various features, the incidence of running injuries has not substantially changed (13) and there is often limited or contrasting evidence that running shoes can alleviate a sustained or self-reported injury (10, 19, 24). This inconclusive evidence does not help to understand the role that running shoes may have on influencing a runner's movement patterns. Furthermore, recent scientific publications have provided new paradigms to improve the understanding of functional aspects of running, running injuries and the role of running shoes (13, 15).

The recently proposed new paradigms include that (a) there exists a "comfort filter" that runners use when selecting a shoe which may be associated with protection against injuries, (b) runners try to stay in a "preferred movement path", a movement path that is assumed to be associated with minimal energy demand and (c) "functional groups" of individuals exist who respond similarly to changes in footwear conditions (13). This paper focuses on the "preferred movement path" paradigm.

The term "movement path" is used to describe the trajectory of joint angles or segment markers during a given movement such as heel-toe running (15). It was proposed that the lower extremity kinematics change only minimally for many different changes in footwear (15). These small changes in kinematics were proposed to be due to the subjects wanting to stay in the same movement path, and that this movement path demands the least amount of energy in the context of the task conditions (15). In fact, the preferred movement path of a runner is not assumed to be constant but is likely sensitive to varying running conditions such as the onset of fatigue, training status, or presence of injury. The concept of the "preferred movement path" was influenced by two key publications: (a) Wilson et al. (28) proposed a "minimal resistance movement path" based on results from cadaver joint movements). (b) Stacoff et al. (22) showed in experiments quantifying the actual skeletal movement for different footwear and insole conditions that the kinematics changed only minimally and not systematically for the different footwear conditions.

Small changes in the magnitude of joint kinematics using skin and shoe mounted markers have been observed at discrete events during the stance phase of running (7, 16, 21), whilst the overall pattern in joint kinematics appeared to remain similar (20). Changes in joint kinematics between running shoes were also joint dependent and often observed across the whole cohort of runners and not on an individual basis. Analysing a mean curve across a cohort of runners, however, provides no specific information. Changes can occur in both directions (increase or decrease), specific differences for individuals are often overlooked and for this reason, each runner should be analysed independently. The small changes in the magnitude of joint kinematics and not in the overall path have helped strengthen the preferred movement path paradigm (15). Furthermore, for the "preferred movement path" paradigm, it is of interest to know what percentage of runners would stay in the same movement path and what percentage would change for any given change in running shoe conditions. The idea of the preferred movement path has recently been implemented in a new movement assessment called "Run Signature", which aims to match running shoes to individual runners (2).

While the general concept of the "preferred movement path" paradigm is clear, many details are still not known or not well understood. For instance, when analysing a runner's joint kinematics we cannot conclude whether or not a movement path is the preferred one. The paradigm assumes that, in general, subjects use a movement path that is close to the preferred one. In order to determine the “preferred movement path” one needs additional information such as the global energy demand and/or comfort assessment (9). If subjects change their movement path when changing running shoes, we assume that this change is made because the new shoe condition has a different “preferred movement path”, rendering the preferred movement path to be shoe and movement dependent. However, it is assumed that for extreme footwear differences, e.g. a mountaineering shoe versus a minimalist running shoe, the joint kinematics should be different and, consequently, the movement paths differ. A more reasonable “extreme shoe condition” is barefoot running, as the joint kinematics for barefoot running are assumed to differ greatly from shod running (1). Therefore, it is unknown if a maintenance of a runner's preferred movement path exists across a large spectrum of running shoe types.

For instance, do changes between conventional running shoes and minimalist running shoes affect the preferred movement path? A second question is whether the actual movement path changes when changing from shod to barefoot.

The aim of this study is to add experimental information to the “preferred movement path” paradigm. More specifically, the purposes of this paper are:

(a) to quantify group differences in lower extremity joint kinematics of runners subjected to different running footwear conditions, and

(b) to quantify individual differences in lower extremity joint kinematics for runners subjected to different running footwear conditions

It was hypothesized that

H1 The “movement paths” in the ankle and knee joint are maintained (i.e. kinematic changes are small) by the majority of runners when running in shoes with similar characteristics.

H2 The “movement paths” in the ankle and knee joint are less maintained (i.e. kinematic changes will be larger) between footwear conditions that possess substantially different characteristics.

Methods

Participants

Thirty-five heel-toe runners (18 males and 17 females, age 29.9 ± 9.7 years, height 171.9 ± 8.1 cm, and weight 69.0 ± 11.7 kg) took part in the study. Runners were required to be injury free six months prior to the time of testing and run at least twice a week. All runners gave written informed consent in accordance with the University of Calgary’s Conjoint Health Research Ethics Board.

Data Collection

Testing took place on a single day in an indoor laboratory and three-dimensional (3D) marker trajectories were collected using an eight camera motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 240 Hz. Sixteen 20 mm retro-reflective markers were skin-mounted on the segments of the forefoot, rearfoot, shank, and thigh of the right lower extremity and the pelvis to measure the three-dimensional movement of these segments. An additional seven markers were placed over the right greater trochanter, medial and lateral knee joint axis, medial and lateral malleoli, and first and fifth metatarsal heads. (Figure 1). Position data were first collected for a static neutral trial for each of the shoe conditions in order to define the segment coordinate system. Subsequently, the joint centre markers were removed for the running trials. The same researcher placed the markers for each running shoe condition.

Insert Figure 1 Near Here

The global coordinate system (GCS) origin (0, 0, 0) was at ground level in the middle of the capture volume. The positive GCS axes were defined from the origin with the X-axis in the direction of running, Y-axis perpendicular to running direction and Z-axis directed vertically upwards. A single force plate (Kistler, 9281CA) was synchronised with the motion analysis system and collected ground reaction force data at 2400 Hz. Timing lights were placed 1.9 m apart along the GCS X-axis to monitor running speed.

Runners performed ten running trials at 3.3 ms^{-1} (± 15%) in three running shoe conditions and one barefoot condition. The three running shoes used were the Mizuno Be, Mizuno Wave Rider and Mizuno Wave Universe. Each running shoe had distinct design features and were categorised as a minimalist shoe (Be, heel-drop < 3 mm, weight approximately 0.2 kg), a conventional cushioned running shoe (Wave Rider, heel-drop approximately 14.1 mm, weight approximately 0.3 kg) and a racing flat (Wave Universe, heel-drop approximately 3 mm, weight approximately 0.11 kg) (Figure 1). The main differences in shoe design between the Be shoe and the Wave Universe were that the Be shoe design included a rounded outer sole and a gap space under the toe area while the Wave Universe incorporated a flat, thin outer sole with a middle groove on the outer sole heel. The four running shoe conditions were tested in a randomized order to avoid order effects.

Data Analysis

Ten running trials per condition were analysed for each runner. Marker trajectories were labelled using Cortex (Motion Analysis, USA) and further processing including model building was performed using Visual 3D (C-Motion Inc, USA). The marker trajectories were filtered using a 4th order low pass Butterworth filter at 10 Hz following residual analysis of raw marker trajectories. The lower limb six degree of freedom model comprised of five segments (pelvis, right thigh, right shank, right hind foot and right forefoot). The origin of each segment's local coordinate system was at the proximal end. The orientation of the local coordinate system was the same for each segment based on the right hand coordinate system with the z-axis directed vertically and y-axis directed anteriorly. Three-dimensional knee and ankle joint angles were calculated as the relative rotation between the thigh and shank segment and the shank and hind-foot segment, respectively, using a XYZ Cardan rotation sequence. Joint angles were expressed relative to the static standing posture by aligning proximal and distal segment coordinate systems. For 3D angles, positive angles represented ankle dorsiflexion, ankle inversion, ankle adduction, knee extension, knee adduction and knee internal rotation.

Each running trial was temporally normalised to the stance phase between touch down and toe-off, which were defined based on when the vertical ground reaction force was above and below a threshold of 10 N respectively.

The mean and standard error (SE) were computed for each joint kinematic variable across ten steps and all 35 subjects. The mean absolute differences across the whole stance phase between two shoe conditions for each joint kinematic variable were quantified across all subjects. Similarly, the mean was computed for each joint kinematic variable across ten steps for each individual and the mean absolute differences across the whole stance phase between two shoe conditions for each joint kinematic variable were quantified for individuals. For the individual subject comparisons, thresholds of 2°, 3° and 5° were selected to show the order of magnitude of the differences. Paired McNemar tests were used to determine changes in the proportion of subjects who displayed kinematic changes between pairs of running shoe condition comparisons. A significant McNemar chi-squared (χ^2) ($P < 0.05$) was an indication of a difference in the proportion of runners who changed their kinematics between pairs of running shoe condition comparisons. The condition comparisons were Rider vs. Universe, Rider vs. Be, Universe vs. Be and Rider vs. Barefoot.

Results

Mean joint kinematics for running shoe comparisons

The mean joint kinematics (Figure 2) showed only small differences between the conventional running shoe (Rider) and the racing flat (Universe). The absolute mean differences across all runners were less than 2.5° for all ankle and knee variables when comparing the Rider vs. Universe, Rider vs. Be and Universe vs. Be joint kinematics.

Insert Figure 2 Near Here

Mean joint kinematics for the conventional running shoe and barefoot

The mean joint kinematics (Figure 3) showed substantial differences between the Rider and barefoot conditions. The mean differences were 4.3° for ankle plantar-dorsiflexion, 3.5° for ankle in-eversion, 3.7° for ankle ab-adduction, 3.7° for knee flexion-extension, 2.1° for knee ab-adduction and 2.4° for knee internal-external rotation. The results showed more dorsiflexion in the ankle joint and more flexion in the knee joint for the conventional running shoe compared to barefoot running.

Insert Figure 3 Near Here

Individual results for the running shoe comparisons

The majority of subjects showed small differences in ankle and knee joint kinematics when comparing the Rider (conventional shoe) versus the Universe (racing flat) (Table 1). The largest number of different movement responses was determined for ankle adduction, with eight subjects showing larger differences than 3° and four subjects showing larger differences than 5°. A significantly greater proportion of subjects changed their ankle inversion by more than 2° between the Rider vs. Be conditions compared to the Rider vs. Universe ($\chi^2 = 3.1$, $P = 0.02$) (Table 1). Similarly, a significantly greater proportion of subjects changed their ankle inversion ($\chi^2 = 9.4$, $P = 0.002$) and knee flexion ($\chi^2 = 4.0$, $P = 0.04$) by more than 2° between the Universe vs. Be conditions compared to the Rider vs. Universe (Table 1).

Insert Table 1 Near Here

Individual results for the conventional running shoe and barefoot

Many of the runners showed ankle and knee joint kinematics that differed between the conventional Rider running shoe and barefoot by more than 3°, especially for ankle dorsiflexion and knee flexion (Table 2). Twenty-eight out of the 35 subjects showed a different movement response (> 3°) for ankle dorsi-flexion. Twenty out of the 35 subjects showed a different movement response (> 3°) for knee flexion. The changes in the corresponding movement variables were larger for the ankle than for the knee joint. The proportion of runners who changed their ankle kinematics changed significantly between the Rider vs. Barefoot and Rider vs. Be for ankle dorsiflexion, ankle inversion (less than 2°, 3° and 5°) and ankle adduction (< 3°). The proportion of runners who changed their knee kinematics changed significantly between the Rider vs. Barefoot and Rider vs. Be for knee flexion, knee adduction (< 2°, 3°) and knee internal rotation (< 5°).

Insert Table 2 Near Here

Discussion

Based on the concept of the preferred movement path it was proposed that when running in similar footwear conditions, the joint kinematics will change minimally (less than 3° and less than 5°). In this paper, the effect of different footwear conditions on ankle and knee joint kinematics was quantified during running. The results indicate that the mean kinematics of the ankle and knee joints were similar between the conventional running shoe (Rider) and both the racing flat (Universe) and the minimalist shoe (Be). Thus the first hypothesis, that the preferred movement path is typically maintained when running in different shod conditions, seems to be supported. A mean curve, however provides no specific information and since the changes can be in both directions (increase or decrease), specific differences across individuals are often overlooked. For this reason, each runner was analysed independently.

The comparison of the individual reactions to the footwear interventions showed that the percentage of runners maintaining their movement path between the conventional and both the racing flat and the minimalist shoe was in the order of magnitude of about 80 to 100%, depending on the joint and the movement component. Thus, it seems appropriate to assume that, when changing within a certain category of shoes, the actual joint movement does not change substantially. Thus, the first hypothesis is supported by these results.

The joint components where we have the best compliance with the “preferred movement path” paradigm were ankle dorsi/plantarflexion, ankle in/eversion and knee ab-adduction. The joint components with the least compliance were ankle ab/adduction and int/ext. knee rotation. There are two possible explanations, a functional and a methodological, for why joint rotations in the transverse plane differed more substantially between shoe conditions compared to joint rotations in the sagittal and frontal plane. From a functional perspective, footwear changes experienced by the subjects may lead to the greatest kinematic response in the transverse plane. Anatomically, the ankle joint only has two axes of rotations, the quasi-medio-lateral ankle axis related to dorsi/plantarflexion and the tilted subtalar joint axis related to pronation/supination (15). Due to the difficulty of quantifying the orientation of the subtalar axis, biomechanical studies typically describe ankle kinematics as rotations about three clinical, orthogonal axes as utilized in this study. Pronation and supination is mostly represented by rotations about the clinical anterior-posterior eversion/inversion axis but also affect rotations in the transverse and sagittal plane. Since changes in ankle inversion/eversion between shoe conditions were minimal (Table 1), it is unlikely that the low compliance of ankle ab/adduction was a functional response to the footwear intervention. Furthermore, when switching from shod running to the extreme condition of barefoot running, the least number of subjects showed a kinematic response in the transverse plane (Table 2), suggesting that ankle and knee joint rotations in this plane are minimally affected by different footwear conditions (1, 22). From a methodological perspective, low compliance of transverse plane joint rotations to the preferred movement path may be due to higher measurement error in this plane. Previous studies that compared three-dimensional ankle kinematics quantified from skin- and shoe-mounted markers to bone-mounted markers reported the highest relative error for ankle ab/adduction and tibial rotation with deviations up to 7° (11, 17). These errors likely originate from soft tissue artefacts and deformation of the shoe, which leads to artificial segment marker movement. Moreover, since the relative joint rotations in the transverse plane were determined last in the XYZ Cardan rotation sequence applied in this study, errors from the sagittal and frontal plane may accumulate and further increase the transverse plane error.

There will be arguments about the threshold value and clinical relevance when comparing joint movement. It was for this reason that the results for 2, 3 and 5° were included. The basis for selecting 2° as the lowest threshold was that differences in joint movement below this threshold fall below the degree of reliability of skin marker-based 3D motion (6). Above 2° readers can, based on their philosophical preferences interpret whichever threshold they prefer. Nevertheless, due to the limited range of motion for some degrees of freedom at the ankle and knee joint, a movement deviation of 3° may be clinically relevant for one joint rotation (e.g. ankle inversion – small range of motion) but not for another (e.g. knee flexion – large range of motion). In this study, the data show that the basic result is the same independent of the threshold: for similar shoes, the majority of the runners do not change their movement path. Many studies comparing different running shoe have been published, often citing small, but statistically significant kinematic differences on the order of 1 to 3° between standard running shoes (3), or between standard and minimalist shoes (27). It is likely that the majority of the subjects remained in their preferred movement path while running in the different shoe conditions. Therefore, it is suggested that the effects of the test conditions on aspects such as running styles or risk of injuries should not be over-interpreted. Future studies should be aimed at determining a joint-dependent threshold value when deviations from the preferred movement path become clinically relevant, e.g. by evaluating clinically meaningful outcomes such as injury risk, fatigue, and running performance.

The results, however, are different when quantifying the differences between the more substantially different conventional running shoe and barefoot running. This comparison showed that the mean kinematics were different, especially for ankle dorsiflexion and knee flexion. As a matter of fact, more than 50% of the tested runners showed a change of the ankle kinematics greater than 3° and about 25% showed a change greater than 5°. Less ankle dorsi-flexion and knee flexion have been observed when comparing running kinematics between barefoot and a running shoe in a previous study, and may serve two potential functions (1). The first was a means of reducing the pressure under the heel to alleviate discomfort, or secondly to reduce the stress across a injurious patellofemoral joint due to a reduced moment arm (1). This study has shown that the changes in joint movement are not just a change in the amplitude while maintaining the original path. It is a change of amplitude and path for a substantial percentage of the runners tested. Thus, the second hypothesis, that the preferred movement path is less maintained when the changes of shoe characteristics are substantial, is supported by the results of this study.

It is assumed that the strategies to maintain the preferred movement path are achieved by finely tuned muscle coordination. Consequently, it is speculated that electromyography (EMG) measurements may provide some indications as to whether or not a certain shoe condition promotes an individual's preferred movement path. There is some evidence that muscle activity differs across footwear conditions (26) and the different muscle activity suggests that internal forces would also be different. Thus, changing footwear likely has an effect on joint and soft tissue loading. A change in joint kinematics (movement path) will also most likely have an effect on running economy, although the effects of cushioning versus shoe mass would need to be considered (23). However, these effects are not yet understood and need further research. Nevertheless, the specific factors that explain the changes in the actual joint movement across conditions have not yet been identified. The important differences may be mechanical or sensorimotor and will most likely be different for different changes in footwear.

Conclusion

Many runners stay in the same movement path (the preferred movement path) when running in various different footwear conditions. The percentage of runners maintaining their preferred movement path depends on the magnitude of the change introduced by the footwear condition.

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Figure 1. Marker set-up including anterior and posterior superior iliac spine (RASI, LASI, RPSI, LPSI), thigh (three markers), shank (three markers), fifth metatarsal, forefoot (three markers) and hindfoot (three markers). Additional markers were added on the right greater trochanter, lateral and medial femoral epicondyles, lateral and medial malleoli, first metatarsal during static trials in order to identify joint centres. The running shoes used in this study were Be (top), Universe (middle) and Rider (bottom).

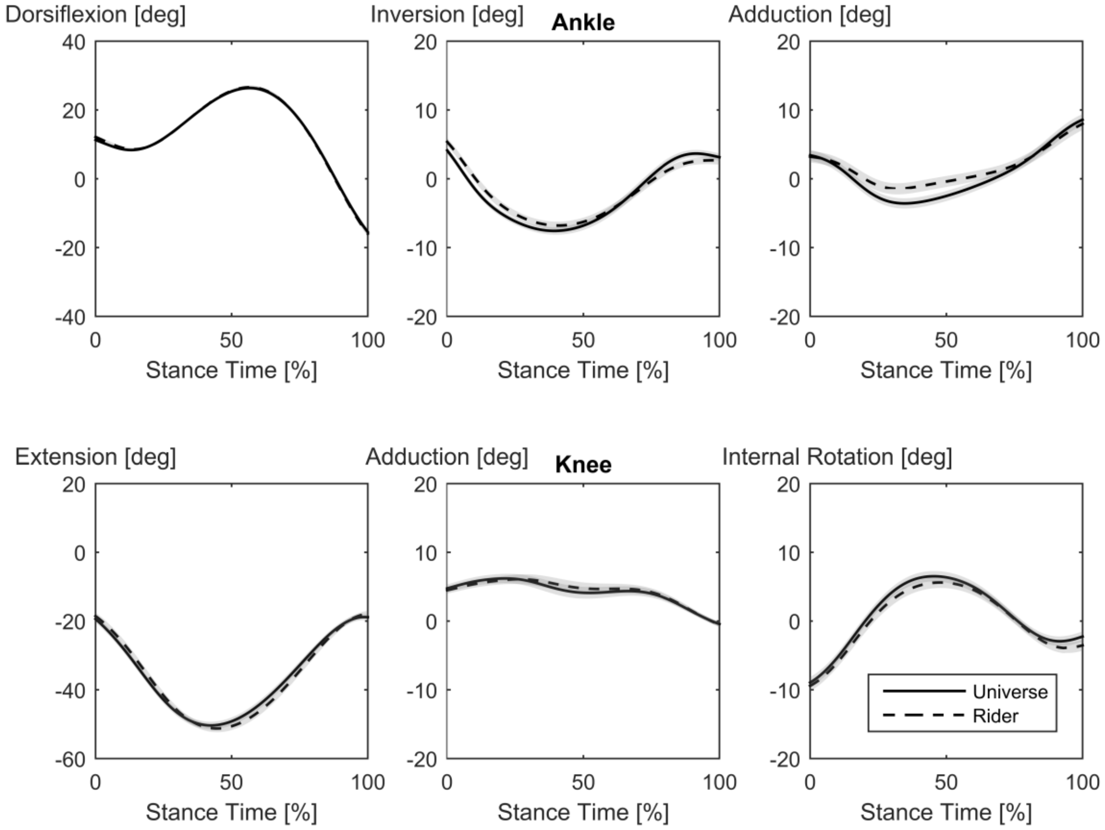

Figure. 2 Mean ± SE (shaded area) results for the ankle (top) and knee (bottom) kinematics for all 35 subjects for the "conventional running shoe" (Rider, dashed line) and the "racing running shoe" (Universe, solid line).

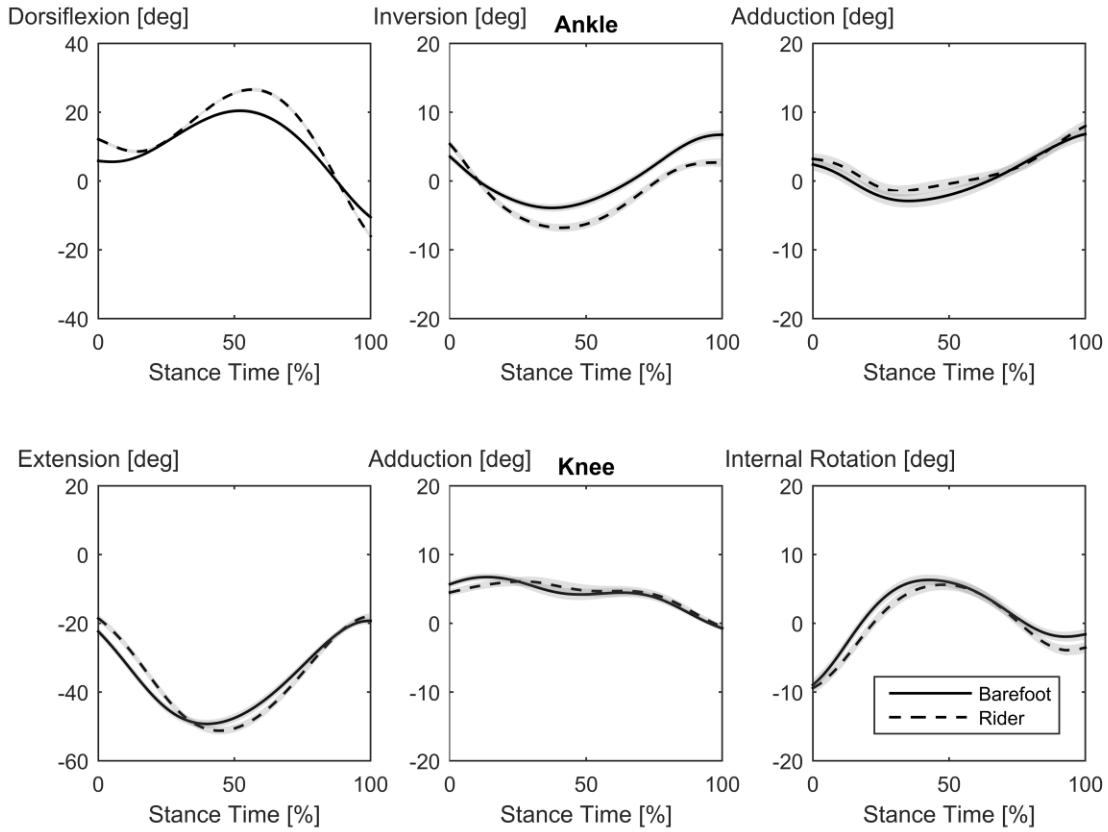

Figure 3. Mean ± SE (shaded area) results for the ankle (top) and knee (bottom) kinematics for all 35 subjects for the two footwear conditions “conventional running shoe” (Rider, dashed line) and “barefoot” (solid line).

Table. 1. Summary of the proportion of subjects (35 in total) (count and percentages) with absolute mean difference in knee and ankle joint kinematics smaller than 2°, 3° and 5° between running shoe comparisons.

Mean Difference	Ankle Dorsiflexion	Ankle Inversion	Ankle Adduction	Knee Flexion	Knee Adduction	Knee Int. Rot.
Rider vs. Universe						
< 2°	26	30[a,c]	25	19[c]	32	27
[%]	74.3	85.7	71.4	54.3	91.4	77.1
< 3°	33	32	27	31	34	30
[%]	94.3	91.4	77.1	88.6	97.1	85.7
< 5°	35	35	31	34	34	33
[%]	100	100	88.6	97.1	97.1	94.3
Rider vs. Be						
< 2°	20	20[a]	18	23[b]	32	25
[%]	57.1	57.1	51.4	65.7	91.4	71.4
< 3°	29	28	29	29	34	30
[%]	82.9	80.0	82.9	82.9	97.1	85.7
< 5°	34	35	33	32	34	33
[%]	97.1	100	94.3	91.4	97.1	94.3
Universe vs. Be						
< 2°	20	16[c]	18	27[b, c]	34	26
[%]	57.1	45.7	51.4	77.1	97.1	74.3
< 3°	30	28	29	31	35	32
[%]	85.7	80.0	82.9	88.6	100	91.4
< 5°	35	35	33	34	35	35
[%]	100	100	94.3	97.1	100	100

[a] Significant difference between Rider vs. Universe and Rider vs. Be ($P < 0.05$).

[b] Significant difference between Rider vs. Be and Universe vs. Be ($P < 0.05$).

[c] Significant difference between Rider vs. Universe and Universe vs. Be ($P < 0.05$).

Table. 2. Summary of all individual mean differences (absolute and percentages) in knee and ankle joint kinematics smaller than 2°, 3° and 5° for all 35 subjects between the Rider and barefoot.

Mean Difference	Ankle Dorsiflexion	Ankle Inversion	Ankle Adduction	Knee Flexion	Knee Adduction	Knee Int. Rot.
< 2°	1 *	11 *	11	4 *	24 *	15 *
[%]	2.9	31.4	31.4	11.4	68.6	42.9
< 3°	7 *	17 *	18 *	15 *	27 *	28
[%]	20.0	48.6	51.4	42.9	77.1	80.0
< 5°	26 *	28 *	27	29	32	32
[%]	74.3	80.0	77.1	82.9	91.4	91.4

* Significant difference to Rider vs. Be ($P < 0.05$).