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## Comparison of Lower Extremity Kinematic Curves During Overground and Treadmill Running

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### Abstract

Researchers conduct gait analyses utilizing both overground and treadmill modes of running. Previous studies comparing these modes analyzed discrete variables. Recently, techniques involving quantitative pattern analysis have assessed kinematic curve similarity in gait. Therefore, the purpose of this study was to compare hip, knee and rearfoot 3-D kinematics between overground and treadmill running using quantitative kinematic curve analysis. Twenty runners ran at  $3.35 \text{ m/s} \pm 5\%$  during treadmill and overground conditions while right lower extremity kinematics were recorded. Kinematics of the hip, knee and rearfoot at footstrike and peak were compared using intraclass correlation coefficients. Kinematic curves during stance phase were compared using the trend symmetry method within each subject. The overall average trend symmetry was high, 0.94 (1.0 is perfect symmetry) between running modes. The transverse plane and knee frontal plane exhibited lower similarity (0.86–0.90). Other than a 4.5 degree reduction in rearfoot dorsiflexion at footstrike during treadmill running, all differences were  $\leq 1.5$  degrees. 17/18 discrete variables exhibited modest correlations ( $>0.6$ ) and 8/18 exhibited strong correlations ( $>0.8$ ). In conclusion, overground and treadmill running kinematic curves were generally similar when averaged across subjects. Although some subjects exhibited differences in transverse plane curves, overall, treadmill running was representative of overground running for most subjects.

### Keywords

biomechanics; gait; waveform comparison

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Instrumented gait analyses are most often conducted overground. However, treadmills are advantageous as they allow the collection of multiple, sequential foot-strikes. It has been suggested that gait mechanics during treadmill (TM) running are different from overground (OG) running. During TM running, the surface moves under the individual, while the individual propels himself over the surface during OG running.

Two studies have examined kinematic differences between OG and TM walking on treadmills instrumented with forceplates. Riley and colleagues (2007) reported lower extremity differences were generally  $\leq 1.5$  degrees between these modes. Their largest difference was at the hip where internal rotation was 2.3 degrees greater during OG walking. Focusing on sagittal plane motion, Lee & Hidler (2008) found that ankle and hip mechanics

were similar between OG and TM walking. However, knee joint excursion was greater during OG gait.

Running kinematics have also been compared between OG and TM locomotion. Both Nigg et al. (1995) and Wank et al. (1998) reported that peak 2-D frontal and sagittal angles were generally similar between these modes of running. However, they both noted that subjects exhibited decreased ankle dorsiflexion at footstrike during TM running. These ankle differences were attributed to a change in strike pattern from rearfoot to midfoot striking. When Nigg et al. (1995) excluded subjects who became midfoot strikers on the TM, they found no significant differences between running modes in the lower extremity. In a 3-D kinematic study of lumbo-pelvic-hip kinematics in 10 runners, Schache et al. (2001) noted reduced hip flexion at footstrike and increased peak hip extension during TM running. Frontal plane peaks and transverse plane range of motion were similar between modes of locomotion. Riley and associates (2008) studied lower extremity motion, 3-D hip, knee and ankle angles, in 20 runners between TM and OG running. They examined maxima and minima across strides, and they did not report any kinematic differences during the stance phase. However, based upon their joint angle graphs, it appears many of the maxima and minima occurred during the swing phase, which indicates that peak angles during stance were not compared.

While these studies suggest kinematics are not different between TM and OG running, there are no comprehensive, three-dimensional comparisons during the stance phase, where loading occurs. Stance is the phase of gait where the lower extremity is most prone to injury and is often the focus of gait studies. In addition, all of the comparisons, to date, have been limited to discrete gait variables. While discrete variables provide information about kinematics, they do not fully describe the movement curves. For example, two curves may have similar peak values but different waveforms. This case occurs when comparing peak dorsiflexion angle, during stance, in runners between midfoot and rearfoot strikers. The peaks are similar, but the kinematic curves are different. Therefore, it is important to examine the overall kinematic curve in addition to the peak values. The kinematic curve analysis could strengthen the previous conclusions that overall, the modes of running are not dramatically different.

Several methods have been used to compare movement curves during gait. Intraclass correlation coefficients (ICC) allow comparisons of discrete values such as peaks or excursions across waveforms (Karamanidis et al., 2003). Coefficients of multiple correlation (CMC) provide a quantitative analysis of the ratio of standard deviation to the mean value across a kinematic curve (Kadaba et al., 1989). One limitation of the CMC measure is that it does not directly compare waveform curves. In addition, this measure is unable to indicate offsets, amplitude differences or phase shifts between identical waveforms. However, a recently developed method, trend symmetry, has emerged that characterizes four features of any waveform (Crenshaw & Richards, 2006). This method first provides a numerical value, which indicates general curve similarity for the entire waveforms. This value is calculated using singular value decomposition of the angular rotation matrices. Next, the ratio of the variability about and along the eigenvector is computed. This number can range between 0–1.0, with 1.0 indicating perfect symmetry. Based upon assessment of a normal population, Crenshaw & Richards (2006) suggested that values  $\geq 0.95$  indicated similar kinematic curves. This method also provides a ratio of overall excursions, mean offsets, and phase shifts between kinematic curves. Therefore, it offers a more complete comparison between kinematic curves of interest. This comprehensive approach to the assessment of gait kinematic curves has not been applied to running nor the comparison of OG versus TM locomotion.

The purpose of this study was to compare 3D lower limb kinematics between OG and TM running utilizing both kinematic curve and discrete variable comparisons. Furthermore, a secondary purpose was to compare the results of each method of analysis. Based upon the existing literature, we hypothesized that kinematic curves, would be generally similar between modes of running. Specifically, we expected trend symmetry values to be  $\geq 0.95$  for all curves. Furthermore, we anticipated footstrike and peak values would be  $\leq 1.5$  degrees different and associated ICC values would be  $\geq 0.8$ . We additionally hypothesized that the results would be similar between the analyses.

## Methods

### Subjects

Twenty healthy, recreational runners (10 males, 10 females,  $25.1 \pm 8.7$  years,  $1.75 \pm 0.11$  m,  $71.0 \pm 14.5$  kg) running at least 10 miles per week were recruited for this study. All subjects were rearfoot strikers, during overground running, confirmed through the strike index (SI),  $SI < 0.34$  (Cavanagh & LaFortune, 1980). The University's Human Subjects Review board approved the study, and all subjects provided informed consent before inclusion in the study. All subjects rated their comfort with TM running. Subjects were required to rate their comfort level at least five out of ten, with zero being totally uncomfortable and ten being extremely comfortable, for inclusion in this study. On average, subjects rated their TM comfort 9/10, with the range from 6.5 to 10. Finally, any subject with a history of cardiovascular disease was excluded from participation.

### Data Collection

All testing took place in the Motion Analysis Laboratory at the University of Delaware. We placed a total of 28 spherical retro-reflective markers on the segments of the right rearfoot, shank, thigh and pelvis with elastic tape (BSN-JOBST, Rutherford College, NC, USA). Specifically, anatomical markers were applied as follows: bilaterally to the iliac crests and greater trochanters, medial and lateral femoral condyles and tibial plateaus, medial and lateral malleoli, and first and fifth metatarsal heads. Shells containing four markers for tracking were placed on wraps secured to the posterior-lateral distal aspect of the thigh and shank segments. The rearfoot was tracked with three markers attached to the shoe around the rearfoot. The pelvis was tracked with bilateral anterior superior iliac spine and sacrum markers. A standing calibration trial was captured before the dynamic running trials, following which the anatomical markers were removed. Subjects wore Nike Air Pegasus footwear (Nike, Beaverton, OR, USA).

Both the TM and OG running assessments took place within the same experimental volume without moving or recalibrating the cameras. The sequence of the two modes was counterbalanced to avoid an order effect. For the OG trials, subjects ran at 3.35 m/s (8 min/mile pace) along a 25 m runway. Speed was monitored by photocells and only trials  $\pm 5\%$  were accepted for analysis. A minimum of five acceptable trials were recorded. For the TM (Quinton Cardiology Inc., Bothell, WA, USA) trials, the subjects first warmed up at a self-selected speed for two minutes. The speed was then increased to 3.35 m/s and the subject ran at that speed for three additional minutes before data collection. Again, a minimum of five trials were collected for analysis. Each trial consisted of at least five stance phases, and the first stance phase with all kinematic data was analyzed. The treadmill trials were collected consecutively with the subjects running continuously until all five trials were collected. Kinematic data were sampled at 120 Hz with a passive motion analysis system (VICON, Centennial, CO, USA).

## Data Analysis

We reduced the 3D OG and TM data using Visual 3D (C-motion, Germantown, MD, USA). The hip joint center was determined functionally (Hicks & Richards, 2005) and the knee and ankle joint centers were determined anatomically. We used a XYZ Cardan sequence rotation to determine all joint angles. All data were low pass filtered with a fourth order zero lag Butterworth filter with a cutoff frequency of 12 Hz. This cut-off frequency was determined from identifying the frequency where 95% of the signal content was maintained. For each subject, we used customized LabVIEW software (National Instruments, Austin, TX, USA), which extracted discrete variables (joint angle at footstrike and peak midstance angle). These discrete variables were extracted from each of the five trials for each of the nine joint angles. Then, we time-normalized and averaged the kinematic curves for each joint angle to create ensemble kinematic curves for each subject during both TM and OG running, respectively. We further averaged each subject's ensemble kinematic curves for each joint angle across subjects for composite TM and OG kinematic curves for each joint angle for visual purposes only.

As the TM was not instrumented, the change in vertical velocity from negative to positive of the distal heel marker was used to identify footstrike (Fellin et al., 2010). Toe-off was determined at the time of peak knee extension. To maintain consistency, this same method was used to determine stance during the OG trials as well. In a validation against OG and TM forceplate data, mean errors for were less than 25 ms for footstrike and 6ms for toe-off (Fellin et al., 2010). These methods were consistent with standard deviations less than 5 ms for footstrike and 10 ms for toe-off.

## Kinematic Curve Analysis

We used the trend symmetry methods of Crenshaw & Richards (2006), to assess the similarity of kinematic curves during OG and TM running within each subject. Individual subject values for each of the four measures that were computed by the trend symmetry method were then averaged across subjects. This method included the calculation of three variables: trend symmetry, range offset, and range amplitude for all three planes of motion. In addition, a fourth variable, phase offset, was calculated for the sagittal plane only. Trend symmetry is unitless and was measured through the use of eigenvectors in the following steps.

1. The mean value of each kinematic curve was subtracted from each individual time-point on the curve.

$$\begin{Bmatrix} X_{Ti} \\ Y_{Ti} \end{Bmatrix} = \begin{Bmatrix} X_i \\ Y_i \end{Bmatrix} - \begin{Bmatrix} X_m \\ Y_m \end{Bmatrix}$$

Each kinematic curve was represented by X and Y, respectively. Subscript i indicated the original data, Ti indicates the translated elements after the data were demeaned, and the mean of each curve was indicated by subscript m.

2. These elements were input into a matrix, which contained each pair of points as a row.
3. Singular value decomposition was applied to this matrix of the demeaned points. This operation multiplied the matrix by its transpose and obtained the eigenvectors.
4. Each row of the resultant matrix was rotated by the angle measured between the eigenvector and the X-axis ( $\Theta$ ). This rotation caused the points to lie about the X-axis.

$$\begin{cases} X_{Ri} \\ Y_{Ri} \end{cases} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{cases} X_{Ti} \\ Y_{Ti} \end{cases}$$

Subscript Ri indicates the rotated elements and subscript Ti indicates the translated elements of each data set.

5. The variability of the points was calculated along both the X and Y axes. Specifically, the X-axis variability was the variability along the eigenvector, and the Y-axis variability was the variability about the eigenvector.
6. The trend symmetry value was calculated by dividing the Y-axis variability (variability about eigenvector) by the X-axis variability (variability along the eigenvector), which was expressed as a percent.
7. This value was subtracted from one. Therefore a value of zero indicated perfect asymmetry, and one, indicates perfect symmetry. Values  $\geq 0.95$  were considered highly similar between modes based upon a sagittal plane normative gait database (Crenshaw & Richards, 2006).

Range offset was measured as the mean difference, in degrees, between kinematic curves. A value of zero indicated the mean value is the same for both kinematic curves, while positive values indicated the OG kinematic curve was larger in amplitude than the TM kinematic curve. Range amplitude was calculated as the ratio of the relative excursion (max value minus min value) between kinematic curves (TM excursion/OG excursion) and therefore unitless. A value of one indicated the kinematic curves have the same excursion and numbers larger than one indicated excursions were greater while running on the TM. The phase offset was calculated for the sagittal plane only as the other planes do not undergo large enough excursions (Crenshaw & Richards, 2006). It is calculated in the following manner. First, one kinematic curve was shifted by a 1% stance increment relative to the other. The trend symmetry number was then calculated. This shifting was repeated for every 1% of stance up to 20% stance in both forward and backward increments. The percentage of stance where the maximum trend symmetry value was identified was designated as the phase offset.

### Discrete Variable Analysis

We examined 3D angles for each orthogonal plane of the rearfoot, knee and hip at footstrike and peak 3D midstance angles within subjects. These discrete variables were analyzed with intraclass correlation coefficients (3, k) and with descriptive statistics. ICCs take into account both the correlation between two numbers as well as the similarity between them.

### Results

Overall, the results indicated the two modes of running were similar. The majority of kinematic curves were visually similar between OG and TM running (Figures 1–3). The visual assessment was confirmed by the trend symmetry analysis, which revealed that the mean trend symmetry value for all kinematic curves was 0.94 (Table 1). The mean range offset for all kinematic curves was 0.2 degrees indicating generally similar mean values between modes of running. The mean range amplitude for all kinematic curves was 0.97 indicating similar excursions of motion between modes of running. The sagittal plane phase offsets were all less than 1%. The group mean values for footstrike and peak demonstrated only small differences (Table 2). When comparing individual differences between modes, again most differences were  $< 1.5$  degrees (Table 3). Only 8/18 of the ICC values were  $>0.8$ .

However, 12/18 were greater than 0.7 and 17/18 were greater than 0.6 (Table 3). It should be noted that lower ICC values were not always associated with the largest differences.

At the rearfoot, while the kinematic curves were quite similar, the discrete variables demonstrated some of the largest differences. The sagittal and frontal plane kinematic curves generally overlaid each other for the majority of stance. The rearfoot transverse plane motions exhibited the same kinematic curves although there was a one degree overall offset between the kinematic curves with the TM kinematic curve values being lower than the OG. In terms of discrete variables, the largest mean difference for individuals was a 4.5 degree decrease in dorsiflexion at footstrike during TM running (Table 3). In addition, the largest individual difference seen was in the rearfoot, which was in 13 degrees less inversion at footstrike during TM running (Table 3). The ICCs at the rearfoot were lower than the hip and knee. None of the values were above 0.80, and only 5/6 ICCs were above 0.60. The frontal plane rearfoot angles at both footstrike and peak were associated with low ICC values (0.42 and 0.75), but, small differences (1.2 and 0.5 degrees) between modes.

For the knee, the sagittal plane kinematic curves were very similar, with only small differences seen in the discrete variables. Knee adduction had the lowest trend symmetry value (0.86) of all joint angles (Table 1). Furthermore, knee transverse plane excursions were 18% less on the TM. All knee joint angles exhibited individual mean differences  $\leq 1.5$  degrees. The ICC values were higher than the rearfoot, with the transverse plane variables and peak knee adduction above 0.80. The ICC values for the other knee variables were  $>0.65$ .

At the hip, motions were visually and quantitatively similar in all three planes. Although the trend symmetry values were above 0.95 for the sagittal and frontal planes, the trend symmetry value was only 0.90 for the transverse plane. For individual subject differences, the largest mean difference for footstrike and peak values was only 1.1 degrees more hip adduction at peak during TM running. The ICC values were all 0.80 and above other than for peak hip flexion, for which the ICC value was only 0.76.

## Discussion

The purpose of this study was to compare both discrete values and overall kinematic curves for 3-D lower limb kinematics between OG and TM running. Furthermore, a secondary purpose was to compare the results of each method of analysis. We hypothesized that kinematic curves would be generally similar between modes. This hypothesis was generally supported as the within subjects analysis demonstrated kinematic curves were similar for a majority of the joint angles. Specifically, for 17 of the 20 subjects, at least 6/9 kinematic curves had trend symmetry values  $\geq 0.95$ . For the secondary planes, the kinematic curves were not always as similar as the sagittal plane. In general, within themselves, subjects are more variable in the secondary planes, which could partially explain the lower trend symmetry values. Overall, the range amplitude, range offset and phase offset indicated the joint angles were similar. However, our analysis at discrete points in the kinematic curves indicated greater differences, which was contrary to our hypothesis of the results being similar. This difference was most notable in the sagittal plane for the rearfoot angle at footstrike.

The ensemble kinematic curves (Figures 1–3) should be interpreted with some caution. They were averaged across subjects for each condition. In contrast, the kinematic curve analysis was conducted by comparing the mean kinematic curves for each subject in each mode of running. Overall, the TM ensemble kinematic curves are within one standard deviation of the OG kinematic curves (Figures 1–3). Because the individual subject kinematic curves



were similar between modes of running, overall, TM running is representative of OG running.

As expected, rearfoot kinematic curves were very similar in both the sagittal and frontal planes of motion. However, during TM running, the ankle was less dorsiflexed at footstrike. This change in footstrike position could be related to a shortened stride length or a change from a rearfoot to a midfoot or forefoot strike pattern, which others have noted. Without an instrumented TM, we were unable to ascertain whether this difference was due to a change in strike pattern. This finding agreed with the results of Wank et al. (1998) and Nigg et al. (1995), who found decreased ankle dorsiflexion at footstrike. Similar to Wank et al. (1998) and Nigg et al. (1995), we observed large variability in rearfoot dorsiflexion among subjects. Riley et al. (2008) found a decreased stride length in only half of their subjects. However, they examined rearfoot, midfoot and forefoot strikers and this cohort only examined rearfoot strikers. Kinematic curves of rearfoot motion in the transverse plane were not as similar as in the other planes as evidenced by the lower trend symmetry value ( $<0.90$ ).

Based on the ICC values, rearfoot motion during TM and OG running was not well correlated. However, these low ICC values were generally associated with relatively small average within-subject differences (with the exception of footstrike dorsiflexion). This apparent inconsistency was due to the large individual differences seen at the rearfoot (Table 3). These results suggested that there were some subjects who ran with large differences between the two modes of running.

Knee kinematic curves between modes of running were most similar for the sagittal plane and least similar for the frontal plane. This finding was supported by the results of Riley et al. (2008), whose ensemble kinematic curves appeared visually to be less similar for the frontal plane compared with the sagittal plane. Despite the noted difference in our frontal plane kinematic curves, our footstrike and peak values were similar between modes of running. Riley and associates (2008) also noted similar results for discrete variables at the knee. However, they chose different variables preventing direct comparisons to their work. The smaller excursions noted in the transverse plane during TM running may be related to a shorter stride length that has sometimes been associated with TM running (Nigg et al., 1995 and Wank et al., 1998).

Hip mechanics during both modes were the most similar of all joints. However, the kinematic curve was less similar for the transverse plane (trend symmetry = 0.90). The absolute differences in discrete variables for all of the planes of hip motion were  $< 1.2$  degrees. This finding was in contrast to the findings of Schache et al. (2001) who reported a 5.6 degree decrease in hip flexion at footstrike during TM running. Riley and colleagues (2008) did not quantify differences in hip flexion at footstrike. In both of these published studies, subjects ran at a self selected speed (mean: 3.99 and 3.84 m/s) OG that was matched during TM running. These speeds were higher than that used in this study.

While mean differences were relatively small, ICC values were not as high as expected. This discrepancy suggests that, on an individual basis, there were subjects with large differences between the two modes of running. Specifically, for each joint angle, maximum individual differences ranged between 4.9 and 13.0 degrees. These large individual differences underscore the fact that while, on average, mechanics are similar between modes of running, there were individual subjects who exhibit fairly large differences. It could be argued that individuals with these large differences might be less comfortable with TM running. However, when looking at these subjects, their comfort levels were high. The results simply suggest that for these subjects, TM running may not be representative of OG running. These

individual differences tended to be higher for footstrike than for peak, which indicated subjects may not always land in the same manner between the modes of running.

Although trend symmetry uses multiple variables to compare two waveforms for a complete analysis, the method does have limitations. Specifically, the method does not address the variability of the waveforms. This method can provide values not representative of the raw data for data that are quite variable. We visually compared each subject's five trials during overground and treadmill running, respectively, to ensure similarity across trials, and feel variability was not an issue for our data.

## Conclusion

Overall, treadmill and overground running are generally similar when averaged across subjects. At the hip, the sagittal and frontal planes were most similar and the transverse plane was slightly less similar in terms of kinematic curves. For the kinematic curves at the knee, the sagittal plane was the most similar while the frontal and transverse planes had trend symmetry values less than 0.90. At the rearfoot, the kinematic curves were most similar for the sagittal and frontal planes with the transverse plane trend symmetry number less than 0.90. However, due to some large individual differences, treadmill running may not be representative of overground running for some subjects.

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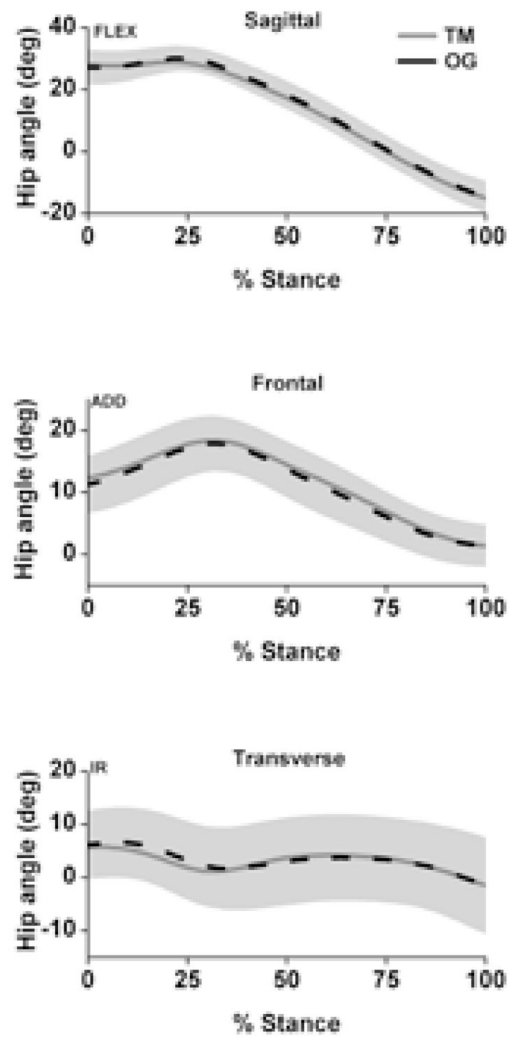
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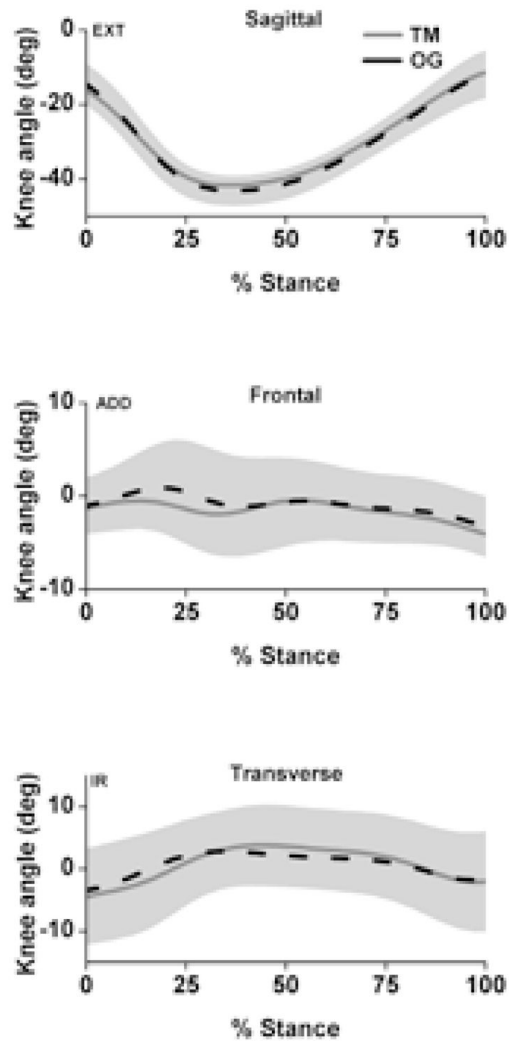
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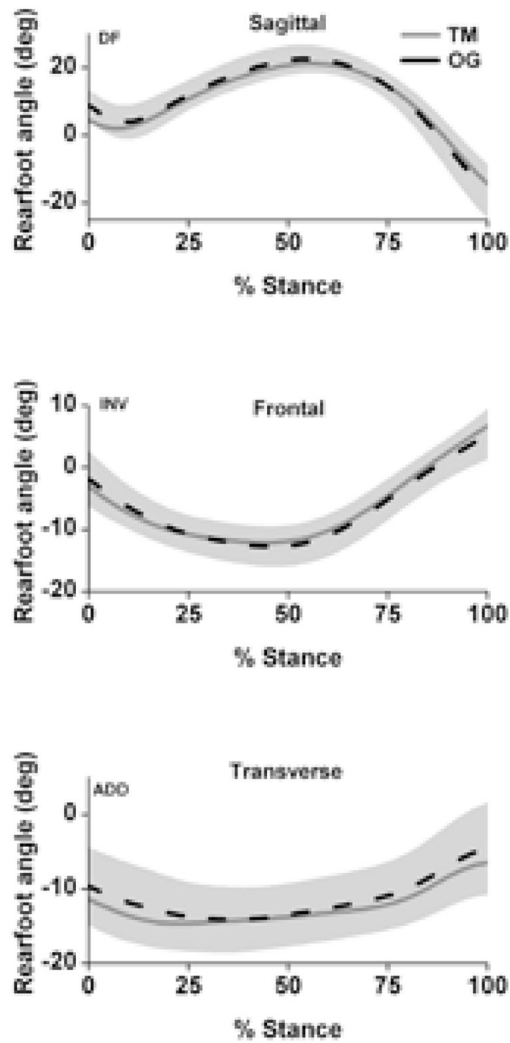
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**Figure 1.** Comparison of hip kinematics between overground, OG (dashed) and treadmill, TM, (solid) running averaged across all subjects. Shaded region denotes the between subjects standard deviation for OG running. Statistical analysis was conducted within subjects. Note the similarities in sagittal and frontal plane motions.



**Figure 2.** Comparison of knee kinematics between overground, OG, (dashed) and treadmill, TM, (solid) running averaged across all subjects. Shaded region denotes the between subjects standard deviation for OG running. Statistical analysis was conducted within subjects. Note the similarity in the flexion curves contrasted with the larger differences, still less than  $2^\circ$ , in the other planes.



**Figure 3.** Comparison of rearfoot kinematics between overground, OG, (dashed) and treadmill, TM, (solid) running averaged across all subjects. Shaded region denotes the between subjects standard deviation for OG running. Statistical analysis was conducted within subjects. Note that subjects land in a less dorsiflexed and more abducted position during TM running compared with OG running although the rearfoot kinematic curves are similar throughout most of stance.

**Table 1**

Trend symmetry values, mean (SD)

	Trend Symmetry (Unitless)	Range Offset (Degrees)	Range Amplitude (Unitless)	Phase Offset (%)
Hip	Sagittal	0.98 (0.00)	0.7 (2.7)	1.00 (0.08)
	Frontal	0.98 (0.00)	-0.7 (2.3)	1.06 (0.14)
	Transverse	0.90 (0.09)	0.2 (1.8)	1.05 (0.43)
Knee	Sagittal	0.99 (0.00)	-0.7 (2.9)	0.96 (0.09)
	Frontal	0.86 (0.12)	0.6 (2.0)	0.96 (0.20)
	Transverse	0.89 (0.14)	0.1 (2.6)	0.82 (0.23)
Rearfoot	Sagittal	0.97 (0.02)	0.7 (2.7)	0.92 (0.12)
	Frontal	0.98 (0.02)	-0.3 (2.0)	1.04 (0.14)
	Transverse	0.89 (0.12)	1.0 (2.0)	0.99 (0.50)
<b>Average</b>	<b>0.94 (0.05)</b>	<b>0.2 (0.6)</b>	<b>0.97 (0.08)</b>	<b>0.0 (0.1)</b>

Note. A positive range offset indicates that the overground (OG) mean value was larger than the treadmill (TM) mean value. A range amplitude greater than 1.0 indicates that OG excursions were larger than TM. A positive phase offset indicates the OG curve was shifted forward, relative to stance time, with respect to the TM curve.

**Table 2**

Comparison of mean angles (in degrees; mean and *SD*) between overground (OG) and treadmill (TM) at footstrike (FS) and peak (PK) during stance at the hip, knee and rearfoot

	Sagittal			Frontal			Transverse		
	TM	OG	Diff.	TM	OG	Diff.	TM	OG	Diff.
FS Hip	28.0 (6.2)	27.2 (5.7)	0.8	12.3 (4.2)	11.3 (4.6)	1.0	5.7 (7.2)	6.2 (6.0)	-0.7
Knee	-16.0 (6.7)	-14.6 (4.9)	-1.4	-1.3 (3.3)	-1.0 (2.8)	-0.3	-3.4 (7.7)	-4.4 (7.4)	1.0
Rearfoot	4.5 (3.7)	9.0 (3.8)	-4.5	-3.0 (3.9)	-1.8 (4.0)	-1.2	-11.4 (4.3)	-9.7 (4.9)	-1.7
PK Hip	30.1 (4.9)	30.8 (4.1)	-0.7	18.7 (4.3)	18.0 (4.4)	0.7	7.1 (7.1)	7.8 (6.3)	-0.7
Knee	-41.9 (4.4)	-43.2 (3.4)	1.3	1.2 (4.5)	2.2 (4.4)	-1.0	4.0 (5.9)	5.2 (5.9)	-1.2
Rearfoot	21.7 (4.0)	22.9 (3.4)	-1.2	-12.5 (3.5)	-12.9 (2.9)	0.4	-16.5 (4.7)	-15.9 (4.0)	-0.6

*Note.* Differences listed are group mean differences, not individual subject differences. Negative difference values indicate TM angle smaller than OG angle. Sign convention: hip flexion, adduction and internal rotation; knee extension, adduction and internal rotation; rearfoot dorsiflexion, inversion and adduction are all positive.



**Table 3**

Within-subject differences (in degrees; mean and *SD*), ICC values, and maximum within-subject differences at footstrike (FS) and peak (PK)

	Sagittal			Frontal			Transverse		
	Avg. Diff.	ICC	Max Diff.	Avg. Diff.	ICC	Max Diff.	Avg. Diff.	ICC	Max Diff.
FS Hip	0.9 (3.2)	0.85	8.1	1.1 (2.8)	0.80	7.6	-0.5 (3.0)	0.90	-5.6
Knee	-1.5 (4.7)	0.67	-8.8	-0.3 (2.6)	0.66	-8.4	1.0 (4.4)	0.83	11.5
Rearfoot	-4.5 (3.3)	0.61	-9.5	-1.2 (4.3)	0.42	-13.0	-1.8 (3.5)	0.71	-7.5
PK Hip	-0.8 (3.1)	0.76	-6.5	0.7 (2.3)	0.86	6.5	-0.7 (2.4)	0.93	-6.0
Knee	1.3 (3.1)	0.68	7.8	-1.0 (2.1)	0.88	-8.7	-1.2 (3.1)	0.86	-6.7
Rearfoot	-1.2 (3.1)	0.65	-7.0	0.5 (2.3)	0.75	4.9	-0.6 (3.3)	0.71	-7.1

*Note.* Negative values indicate treadmill values less than overground values.