A Kinematics and Kinetic Comparison of Overground and Treadmill Running

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ABSTRACT

RILEY, P. O., J. DICHARRY, J. FRANZ, U. D. CROCE, R. P. WILDER, and D. C. KERRIGAN. A Kinematics and Kinetic Comparison of Overground and Treadmill Running. *Med. Sci. Sports Exerc.*, Vol. 40, No. 6, pp. 1093–1100, 2008. **Purpose:** The purpose of this study was to compare the kinematic and kinetic parameters of treadmill running to those of overground running. **Methods:** Twenty healthy young subjects ran overground at their self-selected moderate running speed. Motion capture and ground reaction force (GRF) data for three strides of each limb were recorded and the subjects' average running speed was evaluated. The subjects then ran on an instrumented treadmill set to their average overground running speed while motion capture and GRF data were recorded. The kinematics (body segment orientations and joint angles) and kinetics (net joint moments and joint powers) for treadmill (15 consecutive gait cycles) and overground running (three cycles each limb) were calculated and compared. **Results:** The features of the kinematic and kinetic trajectories of treadmill gait were similar to those of overground gait. Statistically significant differences in knee kinematics, the peak values of GRF, joint moment, and joint power trajectories were identified. **Discussion:** Parameters measured with an adequate instrumented treadmill are comparable to but not directly equivalent to those measured for overground running. With such an instrument, it is possible to study the mechanics of running under well-controlled and reproducible conditions. **Significance:** Treadmill-based analysis of running mechanics can be generalized to overground running mechanics, provided the treadmill surface is sufficiently stiff and belt speed is adequately regulated. **Key Words:** BIOMECHANICS, GROUND REACTION FORCES, INVERSE DYNAMICS, JOINT ANGLES, JOINT MOMENTS, JOINT POWERS

Although treadmills are often used for training, they also can provide a means for a clinician or scientist to evaluate the biomechanics of running under controlled conditions. A new generation of instrumented treadmills has been developed which permit ground reaction force (GRF) to be measured. It is now possible to analyze both the kinematics and kinetics of running on an instrumented treadmill. Instrumented treadmills offer a powerful tool to evaluate running biomechanics. Thus, understanding the kinematics and kinetics of running on an instrumented treadmill as compared to overground running is particularly important.

Before the advent of instrumented treadmills, a number of researchers attempted to compare the kinematics of treadmill and overground running. Elliot and Blanksby (3) reported a shorter unsupported (flight) phase, decreased stride length, and increased cadence in moderate speed (3.3 to 4.8 $m \cdot s^{-1}$) running on a treadmill compared to overground running. Frishberg (4) compared sprint kinematics in five collegiate level sprinters overground (mean velocity 8.54 ± 0.09 $m \cdot s^{-1}$) and on a treadmill (mean velocity 8.46 ± 0.13 $m \cdot s^{-1}$) and found no significant differences in stride frequency, step length, support time, or flight time between the two conditions. Frishberg did, however, report differences in segmental kinematics. The support thigh was more erect at contact and moved with a slower angular velocity, whereas the support shank was less erect at contact and moved with a greater range of motion and angular velocity while sprinting on a treadmill. Nigg et al. (13) reported that runners on a treadmill consistently land with

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a more flat foot than when running overground. In a review of comparisons of treadmill and overground running kinematics and time distance parameters, Williams (22) concluded that the majority of comparisons showed no significant differences and that significant differences only occurred at speeds greater than 5.0 $m \cdot s^{-1}$. Schache et al. (18) reported similar lumbo-pelvic-hip complex three-dimensional (3D) kinematics in treadmill and overground running. Nigg et al. (13) noted that adaptations to treadmill running differ from individual to individual and Lavanska et al. (8) observed that familiarity with treadmill running affects a runner's biomechanics. A number of factors may account for differences in treadmill and overground running: the size and nature of the running surface (6), the procedures used to identify the events of initial contact and toe-off, the treadmill running experience of the subjects, the degree of treadmill accommodation and the tested running speeds (18).

Although the kinematics of treadmill and overground running have been reported to be similar or only slightly different, some believe that the kinetics of treadmill running and overground running are fundamentally different. Winter (23) had noted that the average velocity of the center of mass when running on a treadmill was zero and hypothesized that runners receive energy from the treadmill at foot contact and impart energy to the belt at toe-off. van Ingen Schenau (20), however, showed analytically that if treadmill belt speed is constant and a reference frame moving with the treadmill belt is employed, the mechanics of treadmill and overground running were identical (neglecting only wind resistance). Kram et al. (7) developed a treadmill to measure the vertical and anterior–posterior GRF while running on a treadmill, and a single subject test found that the GRF components of treadmill and overground running at the same speed were very similar, suggesting that the underlying biomechanics are similar.

Although various similarities and differences between treadmill and overground running have been either reported or suggested, there has never been, to our knowledge, a study of joint kinetics, i.e., net joint moments and powers at the hip, knee, and ankle, during treadmill running. Joint kinetic parameters provide insights into the underlying biomechanics of gait such that joint kinetics are now considered an essential component of clinical gait analysis. We (16,17) have shown that, with an adequate instrumented treadmill, it is possible to perform a full inverse dynamic analysis of instrumented treadmill walking to provide calculations of net joint moments and joint powers. The purpose of this study is to present, for the first time, the combined kinematics and kinetics (including joint kinetics) of running on an instrumented treadmill and to compare this data to that collected while running overground. Given the results of our comparison of instrumented treadmill and overground walking (17), we hypothesize that the kinematics and kinetics of instrumented treadmill running will be fundamentally similar to those of overground running.

METHODS

Subjects. Twenty healthy young runners/joggers (10 female) were recruited from the local population. The subjects were regular runners who ran/jogged at least 15 miles each week. Subjects were free of chronic musculoskeletal pathology and had no running-related injury within the last 6 months. The University of Virginia School of Medicine Institutional Review Board approved the testing protocol and written informed consent was obtained from each subject before testing. The average (±1 SD) subject was 25.2 ± 4.6 yr, had an average mass of 66.4 ± 11.2 kg, and was 1.75 ± 0.08 m in height.

Protocol. All testing was conducted in the Department of Physical Medicine and Rehabilitation Gait and Motion Laboratory. Overground running tests were conducted on an approximately 15-m runway. Treadmill running tests were performed on an instrumented treadmill (11,12). Subjects were instructed to run overground trials across the runway at their 10-km race pace. The subjects made practice runs until they felt, and the researchers agreed, that they had accommodated to running on the relatively short runway. Kinematic and kinetic data were then acquired until data for three complete strides of each lower limb were obtained. Immediately after acquisition, a sample of the overground running trials was processed using the standard Vicon event detector and gait cycle parameter estimator to determine the subject's approximate average overground running speed. The instrumented treadmill was then set to the average overground running speed, and the subjects practiced running on the treadmill at that speed for 3 to 5 min. All subjects verbally reported feeling comfortable running on the treadmill at the set speed. Three to five synchronized 30-s recordings of kinematic and kinetic data were then captured. The third trial was used for analysis, the fourth if there were problems with the kinematic data of the third trial. Subjects ran in their personal running shoes.

The same laboratory technician placed all retroreflective markers used for motion capture, and marker placement was unchanged between the instrumented treadmill and overground conditions. Markers on the seventh cervical (C7) and tenth thoracic (T10) vertebrae, on the sternal notch and ziphoid process, and on the left and right acromion processes defined trunk motion. The lower body marker set corresponded to the standard Vicon Plug-in-gait model and is widely used in motion analysis (2,5). Markers on the left and right anterior and posterior superior iliac processes defined the motion of the pelvis. The motion of each lower limb segment was tracked by markers on the lateral femoral condyles, lateral malleoli, lateral midthighs, lateral midshanks, heels, and second metatarsal heads. This set of 22 retroreflective markers defined the 3D kinematics

TABLE 1. Time–distance parameters for treadmill and overground running.

	Overground		Treadmill		Repeated Measures
Time Distance Parameters	Mean	SD	Mean	SD	*P* value
Cadence (1 min^{-1})	170.27	15.77	175.05	11.01	**0.0086**
Walking speed (m·s^{-1})	3.84	0.64	3.80	0.61	0.1161
Stride time (s)	0.71	0.06	0.69	0.04	**0.0011**
Toe off (% cycle)	33.52	2.91	33.26	3.53	0.6860
Stride length (m)	2.71	0.36	2.60	0.36	**0.0001**

Differences that were statistically significant are boldface.

of the trunk and pelvis, and the left and right thighs, shanks, and feet.

Measurements. Kinematic data were recorded using a 10-camera VICON 624 Motion Capture system operating at 120 Hz (Vicon Peak, Lake Forest, CA, USA). The modified whole-body marker set allowed determination of the position and orientation of the pelvis relative to global coordinates. Reported pelvic kinematics are the movements of the pelvis in the laboratory coordinate system. Spine kinematics are movements of the trunk segment in the pelvic coordinate system. Hip angles are rotations of the thigh segments in the pelvis coordinate system, and the remaining lower limb joint angles are rotations of the distal segment in the coordinate system of the proximal segment. Joint moments are reported as internal moments.

GRF data were acquired at the same frequency and in synchrony with the motion capture data. Overground GRF data were acquired using either one of the two in-ground force plates or one of the instrumented treadmill sensors functioning as static force plates. Both the in-ground and instrumented treadmill force plates were produced by AMTI, Watertown, MA, USA. We have previously reported on the characteristics of the instrumented treadmill force plates (16). The instrumented treadmill is an assembly of three treadmill forceplates. Two smaller units (330 mm × 1395 mm) sit side-by-side behind a larger unit (663 mm × 1395 mm) providing a total running surface of 0.66 m wide by 2.795 m long. Because the instrumented treadmill force plates are somewhat larger than the fixed plates, they have slightly lower vertical natural frequencies. The measured vertical resonant frequency of the small units is slightly over 300 Hz and is 219 Hz for the large unit. The nominal vertical resonant frequency of the fixed force plates is 380 Hz. A brushless servomotor rated at 4.7 kW with a 200% 30-s overload capacity drives each treadmill unit. The motors servo on speed and run in synchrony. The measured belt speed variation at foot contact when running at 4 m·s^{-1}

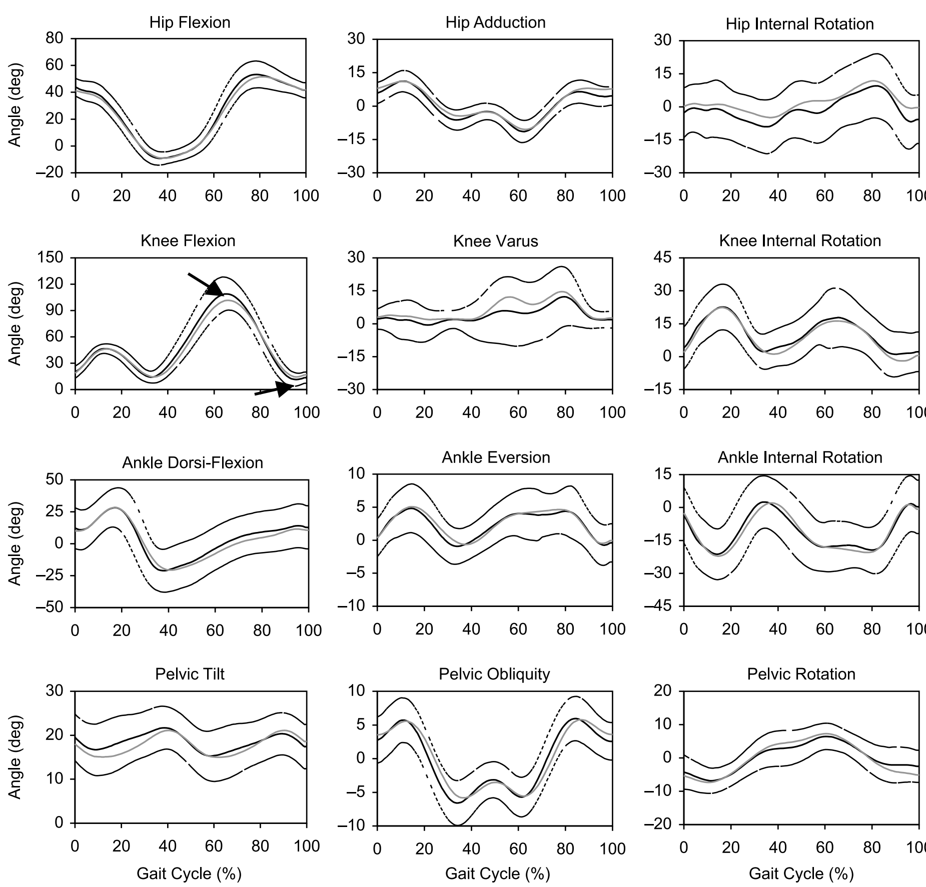

FIGURE 1—3D angular kinematics for overground running (mean, *solid black line*; ± 1 SD, *dotted black lines*) and treadmill running (mean, *gray line*). Angular displacements are in degrees. Arrows indicate peaks found to be significantly different (Table 2).

TABLE 2. Kinematic parameters that multiple repeated-measures ANOVA showed were different ($P < 0.05$) for treadmill and overground running.

Kinematic Parameters	Overground Mean	Overground SD	Treadmill Mean	Treadmill SD	Repeated Measures *P* value
Hip adduction (deg)	12.1	4.1	12.7	4.0	0.0410
Hip int rot (deg)	14.3	12.8	13.0	13.1	0.0455
Hip ext rot (deg)	15.0	12.4	13.2	12.4	0.0488
Knee flx max (deg)	110.1	18.4	103.5	12.2	**0.0005**
Knee flx min (deg)	8.3	6.0	10.2	5.4	**0.0006**
Ankle eversion (deg)	2.5	3.0	1.9	2.9	0.0057
Pelvic rot max (deg)	7.6	3.5	8.5	3.0	0.0186

P values that are statistically significant with a Bonferroni correction ($P < 0.00167$) are boldface.

was less than 7% and was of brief duration because of the fast response of the motor controllers. Only a single unit is required for analysis of running.

Motion capture and GRF data were processed using VICON Plug-in Gait. However, the instrumented treadmill GRF data were preprocessed using in-house algorithms, implemented in LabView (National Instruments, Austin, TX, USA). The preprocessing software detected foot-strikes and toe-offs using a threshold for the vertical component of the force vector of GRF. A threshold setting of 60 N (~10% body weight) (9) was used. However, in some cases, drift exceeded this value for later cycles. We corrected for drift, but only after we had defined the support and contact phases. To get a uniform and adequate number of cycles when drift was a problem, we increased the threshold, not exceeding 150 N (~20%) of body weight. The preprocessor corrected for drift using the flight-phase instrument output as an offset to correct the following stance phase. Instrumented treadmill force plate data were low pass filtered at 30 Hz using a forward and reverse filtering technique (second order Butterworth low-pass filter). An antialiasing filter, also Butterworth, low-pass filtered the static force plate data at 50 Hz. Because of mechanical and electrical noise, somewhat more filtering was required for the instrumented treadmill data to achieve comparable signal to noise characteristics (16). Plug-in-gait calculated the time–distance parameters, pelvis, spinal (trunk relative to pelvis), and lower limb kinematics, the net internal moments for each lower limb joint and the associated joint powers.

Analysis. Individual and group mean parameters were obtained using in-house algorithms developed using LabView. For the overground runs, average time–distance parameters and average plots of kinematic and kinetic parameters were obtained from the six strides recorded (three for each lower limb). For the instrumented treadmill runs, we determined the maxima and minima using one to 30 strides for each subject and graphically examined the stability of the mean as a function of the number of strides. Ten to 12 strides were required to produce a stable estimate of the mean. Results obtained from 15 strides of each lower limb are reported. Maxima and minima of the kinematic and kinetic parameters were extracted from each cycle evaluated and the average over the cycles reported. A total of 30 kinematic and 30 kinetic maximum and minimum parameters were evaluated. For kinematic parameters, the curves for the entire stride were considered. For kinetic parameters, stance phase maxima and minima were determined. The significance of group mean differences in the maxima and minima were evaluated using a multiple repeated-measures ANOVA (SPSS, Chicago, IL, USA). Gender and limb side were between-subject variables in the analysis. Significance was at alpha less than 0.05 and a Bonferroni adjustment was used to correct for multiple measurements (effective alpha < 0.00167).

RESULTS

Time–distance parameters. The average speed of 3.80 $m \cdot s^{-1}$ for instrumented treadmill running was similar to the average overground running speed of 3.84 $m \cdot s^{-1}$ in accordance with the protocol design. The slight difference was because of the variability of overground running speed. If the overground cycles in the analysis did not correspond to the cycles sampled at the time of acquisition, a different overground running speed was obtained. The cadence was significantly higher and the stride time and stride length were significantly shorter when running on an instrumented treadmill (Table 1).

Kinematic parameters. Qualitatively, the kinematics of instrumented treadmill and overground running were very

TABLE 3. Kinetic parameters for which multiple repeated-measures ANOVA showed differences ($P < 0.05$) for treadmill and overground running.

Kinetic Parameters	Overground Mean	Overground SD	Treadmill Mean	Treadmill SD	Repeated Measures *P* value
Hip ext moment ($N \cdot m \cdot kg^{-1}$)	1.74	0.73	1.30	0.88	0.0041
Hip abd moment ($N \cdot m \cdot kg^{-1}$)	0.41	0.21	0.32	0.20	0.0250
Knee flex moment ($N \cdot m \cdot kg^{-1}$)	2.33	0.81	1.70	0.51	<**0.0001**
Knee varus moment ($N \cdot m \cdot kg^{-1}$)	1.90	0.57	1.54	0.53	**0.0001**
Ankle plantarflex moment ($N \cdot m \cdot kg^{-1}$)	3.44	0.70	4.01	0.56	<**0.0001**
Hip power absorption ($W \cdot kg^{-1}$)	6.93	3.81	4.46	3.57	0.0020
Knee power generation ($W \cdot kg^{-1}$)	11.26	4.39	7.63	2.54	<**0.0001**
Knee power absorption ($W \cdot kg^{-1}$)	12.12	4.28	9.47	3.40	0.0020
Ankle power absorption ($W \cdot kg^{-1}$)	8.00	3.23	10.38	3.24	<**0.0001**
Anterior GRF (% body weight)	37.07	11.55	30.75	4.86	**0.0008**
Medial GRF (% body weight)	10.94	4.73	8.29	2.73	**0.0003**
Vertical GRF (% body weight)	263.43	45.20	249.34	21.83	0.0205

Again, *P* values that are statistically significant with a Bonferroni correction ($P < \sim 0.0167$) are boldface.

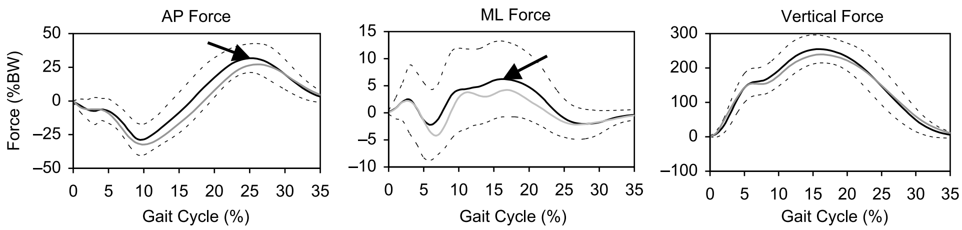

FIGURE 2—3D GRF in stance for overground and treadmill running. Forces are in percent body weight. Again, arrows indicate significantly different peaks (Table 3).

similar (Fig. 1). Quantitatively, condition (instrumented treadmill vs overground) had a significant effect on kinematics (P = 0.022), as did gender (P = 0.046), whereas side did not (P = 0.678). Of the 30 kinematic parameters considered, seven showed differences for condition (P < 0.05), but after the Bonferroni correction only two, peak knee flexion and extension, were statistically significantly different (Table 2). Spine kinematics are not shown in Figure 1 as there were no significant differences found among these angles. All average joint angle curves for instrumented treadmill running were within one SD of the corresponding overground joint angle curve (Fig. 1).

Ground reaction forces. The peak propulsive anterior and peak medial GRF were significantly reduced in instrumented treadmill running (Table 3). Because of the low sampling rate (120 Hz) a well defined vertical force impact peak was not demonstrated in either the instrumented treadmill or overground running condition. The average vertical force during the instrumented treadmill trials was 99.5% of body weight.

Kinetic parameters. Qualitatively, the joint internal moment and power curves were similar for instrumented treadmill and overground running, with similar patterns and timing of peaks and troughs (Fig. 3). Quantitatively, condition had a significant effect on peak kinetic parameters, including GRF (P < 0.001), as did gender (P = 0.009). Again, limb side had no significant effect (P = 0.273). Of the 24 joint moment and power parameters

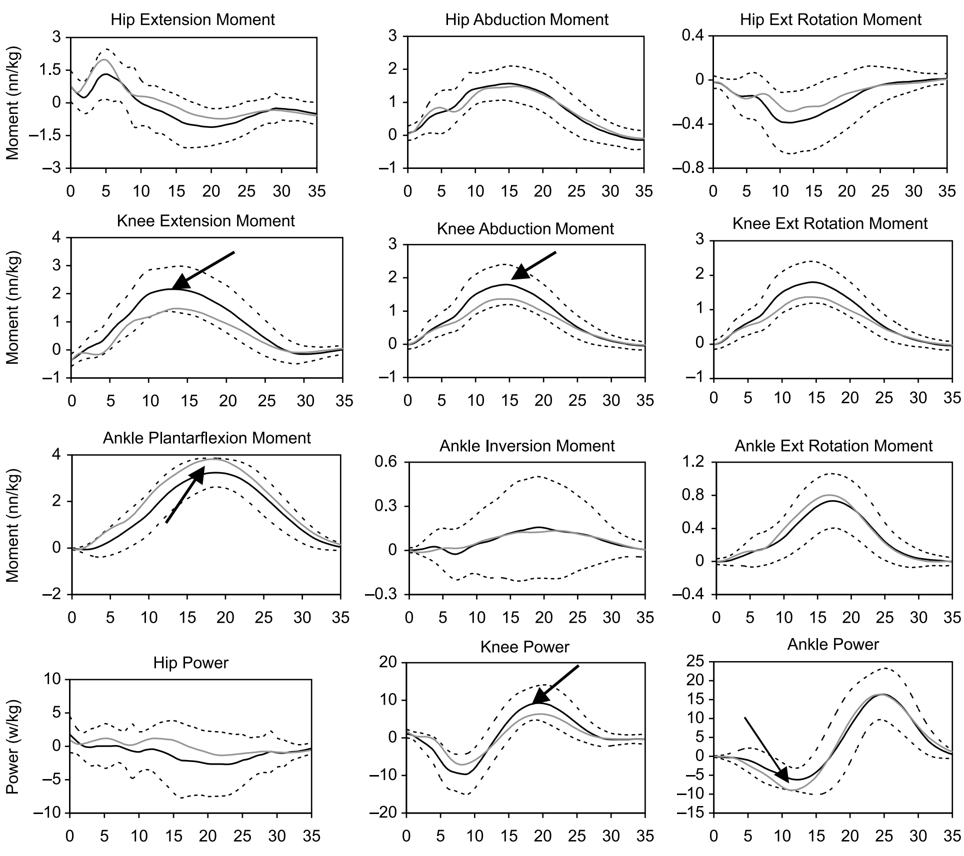

FIGURE 3—3D moments and joint powers in stance for overground running (*black*) and treadmill running (*gray*). Internal moments are normalized to body mass ($N \cdot m \cdot kg^{-1}$) as are joint powers ($W \cdot kg^{-1}$). Arrows indicate peaks found to be significantly different (Table 3).

considered, nine showed instrumented treadmill-overground differences ($P < 0.05$) and seven of these were significantly different when the Bonferroni correction was applied (Table 3). The instrumented treadmill moment and power curves lie within one SD of corresponding overground curves. However, for six of the seven moment and power parameters that were significantly different, there was no overlap of the 95% confidence intervals of the peak values.

Effect of cadence change. It is possible that the significant differences in the peak kinetic parameters occurred simply because the subjects chose to run at a higher cadence and lower stride length on the instrumented treadmill. To test this idea, the subjects were sorted into two equal groups. The high cadence change group ran at a 14 ± 7 steps·min^{-1} higher cadence on the instrumented treadmill, whereas the low cadence change group ran at only 3 ± 2 steps·min^{-1} faster on the instrumented treadmill. For these two groups, the parameters significantly different among all subjects were compared using paired *t*-test between conditions. Overall, fewer parameters were significantly different ($P < 0.05$) because of the smaller number of subjects and the lower precision of the *t*-test. However, most of the kinetic parameter differences were still present in both groups (Table 4).

DISCUSSION

The mean kinematic and kinetic parameter curves of instrumented treadmill running were within one SD of the corresponding overground curves, indicating that instrumented treadmill and overground gait are similar. Comparisons using repeated-measures ANOVA did reveal significant differences between the two running conditions, particularly with regard to the kinetics. The differences in stride length and cadence that we found have been reported in other studies (3,18,21). Our protocol precluded determining if subjects had a different preferred speed for instrumented treadmill running compared to overground running. The speed of instrumented treadmill running was slightly slower that that of overground running, but the difference was not statistically significant. With the exception of sagittal plane peak knee angles, we found similarity of angular kinematics consistent with previous studies (18,22). A comparison of overground and instrumented treadmill running, based on the inverse-dynamics approach to determine joint kinetics (here, to estimate net joint moments and joint powers during running), has not been previously reported. Novacheck (15) studied overground running using a similar marker set, kinematic model, and kinetic analysis. Novacheck's group ran at an average of 3.2 m·s^{-1}, somewhat slower than our group (3.8 m·s^{-1}). Our sagittal plane kinematics and kinetics are similar to those reported by Novacheck. The major exception was ankle plantarflexion moment which appears to differ from both our instrumented treadmill and overground results. This difference may be because of the differences in the subject population (Novacheck's group were all heel-toe runners whereas ours included midfoot and fore-foot strikers. Also, some of our runners reached speeds that Novacheck would have classified as sprinting (>3.9 m·s^{-1}).

Among the kinematic parameters, only the differences in peak knee sagittal plane angles for instrumented treadmill and overground running were statistically significant. Matsas et al. (10) observed a similar difference in knee kinematics between treadmill and overground walking, but reported that the difference vanished after sufficient familiarization with treadmill ambulation. All of our subjects had some experience with treadmill running and were allowed to accommodate to treadmill running for several minutes, until

TABLE 4. Reanalysis of the statistically significant parameters from Tables 2 and 3 for two groups of subjects, those with only a small increase in cadence when running on the treadmill and those with a large increase in cadence.

	High Cadence Change group (14 ± 7 steps·min^{-1})					Low Cadence Change Group (3 ± 2 steps·min^{-1})				
	Overground		Treadmill		Paired *t*-test	Overground		Treadmill		Paired *t*-test
Parameters	Mean	SD	Mean	SD	*P* value	Mean	SD	Mean	SD	*P* value
Hip adduction (deg)	10.9	3.2	10.5	3.4	0.5021	13.4	3.1	13.4	3.0	0.9676
Hip int rot (deg)	16.9	9.1	13.6	10.8	**0.0094**	11.7	14.1	10.6	13.8	0.2757
Hip ext rot (deg)	13.3	11.9	11.6	11.5	0.3361	16.6	10.9	12.9	9.1	**0.0116**
Knee flx max (deg)	117.9	17.7	105.5	13.9	**0.0025**	102.2	16.0	100.1	11.0	0.4531
Knee flx min (deg)	10.3	5.9	13.3	3.9	**0.0111**	6.2	4.8	8.0	4.5	**0.0083**
Ankle eversion (deg)	2.2	2.5	0.8	1.8	**0.0052**	2.9	2.8	2.5	2.8	0.2147
Pelvic rot max (deg)	7.2	2.7	6.0	2.7	**0.0153**	8.7	2.7	8.4	2.0	0.5683
Hip ext moment (N·m·kg^{-1})	1.6	0.7	1.1	0.4	**0.0131**	1.9	0.6	1.2	0.3	**0.0086**
Hip abd moment (N·m·kg^{-1})	0.4	0.2	0.3	0.1	**0.0240**	0.4	0.2	0.3	0.1	0.0527
Knee flex moment (N·m·kg^{-1})	2.3	0.8	1.6	0.4	**0.0023**	2.3	0.5	1.7	0.5	**0.0004**
Knee varus moment (N·m·kg^{-1})	1.9	0.5	1.5	0.4	**0.0311**	1.9	0.5	1.5	0.5	**0.0015**
Ankle plantarflex moment (N·m·kg^{-1})	3.8	0.6	4.2	0.6	**0.0049**	3.1	0.4	3.7	0.4	**<0.0001**
Hip power absorption (W·kg^{-1})	6.5	3.2	3.9	2.2	**0.0033**	7.3	3.7	3.3	1.2	**0.0059**
Knee power generation (W·kg^{-1})	11.4	4.2	7.4	2.0	**0.0033**	11.1	3.4	7.9	2.7	**0.0022**
Knee power absorption (W·kg^{-1})	12.2	4.5	8.6	2.2	**0.0277**	12.0	2.4	8.4	2.1	**0.0005**
Ankle power absorption (W·kg^{-1})	9.7	3.0	11.6	3.0	**0.0289**	6.3	1.7	9.0	1.9	**0.0005**
Anterior GRF (% body weight)	40.9	11.6	32.0	4.7	**0.0276**	33.3	6.4	31.3	5.2	0.0625
Medial GRF (% body weight)	12.2	4.1	8.3	2.2	**0.0163**	9.7	3.5	7.6	2.2	0.0678
Vertical GRF (% body weight)	275.6	43.0	254.5	28.4	0.0917	251.2	19.2	243.3	13.1	**0.0285**

Paired *t*-tests were used to identify between condition differences in the subgroup data.

they reported and appeared to be comfortable. However, they did not all have the 6- to 14-min familiarization period recommended by Matsas et al. (10).

The kinetic parameters exhibit several significant differences. The peak propulsive force and peak medial force are reduced. The reduced knee moments are consistent with the reduction in GRF components but the increased ankle dorsiflexion moment is not. This apparent inconsistency may be because of the subtle differences in foot kinematics previously reported by Nigg (13). Overall, our hypothesis that the kinetics of instrumented treadmill and overground running are similar is not entirely supported. The higher ankle moments and preserved power observed in instrumented treadmill running, however, should put to rest the notion that treadmill running lacks push-off. Preservation of push-off was also observed in our comparison of instrumented treadmill and overground walking (17).

There were several limitations to this study. Although the number of subjects tested was reasonable, there was variability in running style and running speed among the subjects. The self-selected running speeds of our subjects varied from jogging to sprinting and there were mid-foot and fore-foot contactors in the group. Speed and contact style can affect the kinematics and kinetics of running. The subjects wore their own shoes, which varied in style and condition. Shoes may have an effect on running dynamics (1,11,12,14,19). However, repeated-measures analyses were used; the subjects used the same shoes and running style on the instrumented treadmill as when running overground.

The data from the overground portion of the protocol were affected by a number of inconsistencies, some specific to our laboratory and protocol, some inherent to overground testing. Because of the relatively short runway, we could not be certain that overground running parameters were measured at a steady-state condition, whereas near steady-state conditions (± a small amount of drift) were assured for measures on the instrumented treadmill. Trials in which the subject was observed to be accelerating or slowing down were rejected, as were trials with asymmetric braking and propulsive AP GRF data. However, the subjects had been accelerating a stride or two before being analyzed and would be decelerating in a stride or two. Thus, overground data are not a steady state but the apogee of a dynamic trajectory. This is true for overground data acquired on a track as well as on a straight runway because on a track the subject is coming out of and entering into a curve, possibly with a banked surface, before and after data acquisition. Also, the speed of each subject's overground running trials varied slightly, with the average reported. Instrumented treadmill speed was matched to each subject's overground speed and constant (again ± a small amount of drift) for all analyzed data. Because of mechanical and electrical noise, a higher vertical GRF threshold was used to detect foot contact on the instrumented treadmill. However, a variety of techniques used to determine foot contact in overground data is perhaps more problematic. Vertical GRF thresholds are used for clean force plate strikes, computer matching of foot marker trajectories was used in the absence of force plate data, and visual analysis of the kinematics was used to resolve inconsistencies. Three cycles per limb were used to determine the characteristics of overground running, while fifteen were used for instrumented treadmill running. Qualitative analysis of the stability of the mean for instrumented treadmill data indicated that using 10 to 12 cycles or more was desirable. Although it would have been possible to obtain more cycles of overground data, it is certainly more convenient to obtain many cycles on an instrumented treadmill. All foot contacts in the instrumented treadmill data set were with the same surface with the same rigidity. In overground running, the subjects contacted a walkway and in-ground force plates covered with the same thin carpet material, but with somewhat different stiffness, and the instrumented treadmill force plates, covered by smooth belts with rigidity similar to, but slightly different from, the in-ground force plates. In overground trials, slip did not appear to be a problem either with the instrumented treadmill forceplate belts or the in-ground forceplate covering.

What factors contribute to the differences? Van Ingen Schenau (20) established the requirement for constant instrumented treadmill belt speed, which is not strictly met by our device nor likely by any other. Speed variations can be minimized by using a robust motor and belt drive and careful maintenance, but cannot be completely eliminated. However, the speed variations we were able to measure were small and very brief, one or two sample times. Speed variations occurred around the time one would expect the impact peak. Had we seen an impact peak in the overground data, but not in the instrumented treadmill data, this would have been the likely cause. However, neither data set evidenced a well-defined impact peak. The kinetic differences occurred at times when belt speed was well controlled. Any effect of speed variation would have been indirect because of the subject's adaptation to the treadmill, for example.

We did not provide as much accommodation time for treadmill running as Matsas et al. (10) recommended, but our analyses are based on the third or, in some cases, the fourth 30-s instrumented treadmill trial for each subject. Because each trial took a bit more than a minute, (30 s for the actual data acquisition and 30+ s for data processing and storage), it is fair to say that all subjects had 5 min to accommodate to instrumented treadmill running before the analyzed data were acquired. Accommodation to running on a short runway was also an issue. Each subject made several practice runs and several runs were made to obtain three complete cycles with clean force plate data for each limb. There are indications that, beyond the need for accommodation, there is simply a tendency to adapt a slightly different running pattern on a treadmill. The fact that half of our subjects ran at the same stride length and cadence as well as speed on the instrumented treadmill indicates that it is biomechanically possible to do so. The fact that half of our subjects ran with a very different stride length and cadence indicates that it is equally possible to adopt a different strategy. Just as people may adopt a different running pattern on a treadmill, so also do they tend to adopt different running patterns when bare foot or in various shoes, when running on a compliant track or on hard pavement, or when running straight or on a curve. In studying the biomechanics of running, the question is not which running pattern is normal; all are normal for their condition. The concerns are: (1) is the condition representative of the overall task? (2) Can the conditions be controlled and reproduced within and between subjects? With a well-designed, built, and maintained instrumented treadmill, the answer to both of these questions is yes. Thus, we believe that the use of instrumented treadmills to study running is justified, and that such studies will make important contributions to understanding the biomechanics and physiology of running.

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