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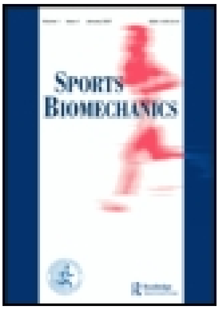
Jim D Richards
University of Central Lancashire

Sarah Jane Hobbs
University of Central Lancashire



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Jonathan Sinclair [a], Jim Richards [b], Paul J. Taylor [c], Christopher J. Edmundson [a], Darrell Brooks [a] & Sarah J. Hobbs [a]

[a] Division of Sport, Exercise and Nutritional Sciences, University of Central Lancashire, Preston, UK

[b] Department of Allied Health Professionals, University of Central Lancashire, Preston, UK

[c] School of Psychology, University of Central Lancashire, Preston, UK

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Three-dimensional kinematic comparison of treadmill and overground running

JONATHAN SINCLAIR[1], JIM RICHARDS[2], PAUL J. TAYLOR[3], CHRISTOPHER J. EDMUNDSON[1], DARRELL BROOKS[1], & SARAH J. HOBBS[1]

[1]*Division of Sport, Exercise and Nutritional Sciences, University of Central Lancashire, Preston, UK,* [2]*Department of Allied Health Professionals, University of Central Lancashire, Preston, UK, and* [3]*School of Psychology, University of Central Lancashire, Preston, UK*

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Abstract
The treadmill is an attractive device for the investigation of human locomotion, yet the extent to which lower limb kinematics differ from overground running remains a controversial topic. This study aimed to provide an extensive three-dimensional kinematic comparison of the lower extremities during overground and treadmill running. Twelve participants ran at 4.0 m/s (±5%) in both treadmill and overground conditions. Angular kinematic parameters of the lower extremities during the stance phase were collected at 250 Hz using an eight-camera motion analysis system. Hip, knee, and ankle joint kinematics were quantified in the sagittal, coronal, and transverse planes, and contrasted using paired *t*-tests. Of the analysed parameters hip flexion at footstrike and ankle excursion to peak angle were found to be significantly reduced during treadmill running by 12° ($p = 0.001$) and 6.6° ($p = 0.010$), respectively. Treadmill running was found to be associated with significantly greater peak ankle eversion (by 6.3°, $p = 0.006$). It was concluded that the mechanics of treadmill running cannot be generalized to overground running.

Keywords: *Biomechanics, joint angles, stance, gait*

Introduction

Many studies investigating the mechanics of human locomotion have been conducted using the treadmill. The treadmill presents an environment where variables such as velocity and gradient can be standardized and reproduced consistently (Schache et al., 2001). Furthermore, the treadmill also allows a greater number of gait cycles to be captured and ensures that continuous movement kinematics are obtained. Thus, the treadmill may facilitate a more repeatable pattern of movement in comparison with the short discontinuous trials associated with overground analyses (Fellin, Manal & Davis, 2010a). Although this is advantageous, it must be demonstrated that the treadmill does not alter the mechanics of the examined movements in comparison with overground motion (Brand & Crowninshield,

Correspondence: Jonathan Sinclair, Division of Sport, Exercise and Nutritional Sciences, Centre for Applied Sport and Exercise Sciences, University of Central Lancashire, Preston, Lancashire PR1 2HE, UK, E-mail: jsinclair1@uclan.ac.uk

1984). There remains debate regarding the assumption that treadmill running approximates overground running. A number of investigations have been conducted examining the biomechanical differences between the two conditions (Frishberg, 1983; Gamble, Bartlett & Jakeman, 1988; Nigg, De Boer & Fisher, 1995; Schache et al., 2001; Riley et al., 2008; Fellin et al., 2010a); the results however are often conflicting.

Using a theoretical literature review, Van Ingen Schenau (1980) proposed that the mechanics of overground and treadmill locomotion are similar, provided that velocity is maintained. A number of studies have examined the kinematic differences between overground and treadmill walking. Lee and Hidler (2007) established that peak flexion and extension measures of the lower extremities did not differ between the two conditions. It has been previously documented that lower limb kinematics in the sagittal plane are comparable between overground and treadmill locomotion (Alton, Baldey, Caplan & Morrissey, 1998; Matsas, Taylor & McBurney, 2000; Riley, Paolini, Della Croce, Paylo & Kerrigan, 2007). Strathy, Chao and Laughton (1983) found that knee joint angular kinematics in the coronal and transverse planes did not differ significantly between the two conditions. Previous analyses have, however, documented significantly greater hip range of motion and flexion angles during treadmill locomotion (Alton et al., 1998; Riley et al., 2007).

Running kinematics has also been compared between treadmill and overground locomotion. Overground running is associated with increased hip flexion at footstrike (Frishberg, 1983; Gamble et al., 1988; Schache et al., 2001), whilst Schache et al. (2001) found no alterations in transverse plane hip motion between the two conditions. There is currently a paucity of information regarding the three-dimensional (3D) kinematics of the lower extremities during treadmill and overground running. Riley et al. (2008) examined the differences in hip, knee, and ankle joint kinematics between treadmill and overground running. However, they examined only maximum and minimum angles of the full gait cycle; therefore, as the majority of these occurred during the swing phase, angles during the stance phase were not compared. Similarly, Fellin et al. (2010a) investigated lower extremity motion during both treadmill and overground locomotion; their examination utilized a trend symmetry design which is an effective method of comparing the similarities between kinematic curves, but it does not examine the differences in lower extremity angulation between the two conditions. Furthermore, investigations that have been conducted to date have been restricted to discrete kinematic parameters, and have thus failed to consider the range of motion, excursions from footstrike to peak angle, or peak angular velocities during stance.

The aim of the current investigation was to assess the extent to which the 3D kinematics from the stance phase of overground and treadmill running are similar. The 3D kinematics of the lower extremities were observed during overground running and compared with the corresponding data from the treadmill.

Methods

Participants

Eleven males and one female who were free from musculoskeletal injury volunteered to take part in this study, and the mean age, height, and body mass were 22.5 ± 4.2 years, 1.71 ± 0.06 m, and 75.4 ± 8.4 kg, respectively. Participants were active recreational runners engaging in training at least three times per week whilst completing a minimum of 25 km per week and had previous experience of treadmill running. Participants encompassed a range of footstrike characteristics. An *a priori* power analysis was conducted using the Hopkins method based on a moderate effect size and a power measure of 80%, which suggested that 12 subjects were adequate for the design. The study was approved by the School of Psychology Ethical Committee, and all participants provided a written informed consent.

Procedures

All kinematic data were captured at 250 Hz via an eight-camera motion analysis system (Qualisys^{TM} Medical AB, Goteburg, Sweden). Two identical camera systems were used to collect each mode of running. Calibration of the Qualysis^{TM} system was performed before each data collection session. To ensure that high-quality kinematic data were obtained, only calibrations producing average residuals of <0.85 mm for each camera for a 750.5 mm wand length and points above 4,000 in all cameras were accepted prior to data collection. The order in which participants performed in each condition was counterbalanced.

The marker set used for the study was based on the calibrated anatomical systems technique using a 6 degree-of-freedom model (Cappozzo, Catani, Leardini, Benedeti & Della Croce, 1995). A static trial was conducted with the participant in the anatomical position, allowing the positions of the anatomical markers to be referenced in relation to the tracking clusters. The anatomical markers were removed after the static trial was captured. Markers used for tracking remained in place for the duration of the treadmill and overground analyses.

Retro-reflective markers were attached to the first and fifth metatarsal heads; medial and lateral malleoli, calcaneus, medial, and lateral epicondyle of the femur; greater trochanter of the right leg; iliac crest; anterior superior iliac spines (ASIS); and posterior superior iliac spines (PSIS) with tracking clusters positioned on the shank and thigh. The hip joint centre was determined using regression equations based on the positions of the ASIS and PSIS markers (Bell, Brand & Pedersen, 1989). Each rigid cluster comprised four 19-mm spherical reflective markers mounted to a thin sheath of lightweight carbon fibre with length-to-width ratios of 2.05:1 and 1.5:1 for the femur and tibia, respectively (Cappozzo, Cappello, Della Croce & Pensalfini, 1997). Participants wore the same footwear throughout (Saucony pro grid guide 2), in sizes 6–9.

The treadmill did not feature an integrated force platform; therefore, footstrike and toe-off events during both treadmill and overground running were determined using the kinematic data based on the method of Dingwell, Cusumano, Stenard and Cavanagh (2001). Footstrike was deemed to be the first occurrence of peak knee extension, and toe-off was determined as the second occurrence of the peak knee extension.

In the overground condition, participants ran at 4.0 m/s in one direction across a 22-m-long laboratory floor (Altrosports 6 mm, Altro Ltd, Letchworth Garden City, Hertfordshire, UK). Running velocity was monitored using infrared timing gates (Newtest 300, Newtest, Oulu, Finland). A maximum deviation of $\pm 5\%$ from the pre-determined velocity was allowed. Runners completed a minimum of six successful trials. A successful trial was defined as one within the specified velocity range, where all tracking clusters were in view of the cameras and with no evidence of gait modification due to the experimental conditions.

A Woodway^{TM} (ELG, Weil am Rhein, Germany) high-power slatted treadmill maintained at a gradient of 0% was used throughout. Participants were given a 5-min habitation period, in which participants ran at the determined velocity. The treadmill was then stopped for 30 s and participants dismounted the treadmill before mounting the treadmill for data analysis in accordance with the recommendation of Alton et al. (1998). When participants indicated that they were ready to begin, the treadmill was restarted and the velocity of the belt was gradually increased until the speed matched with that of the overground condition (4.0 m/s).

Data processing

Trials were processed in Qualisys Track Manager in order to identify anatomical and tracking markers and then exported as C3D files. Kinematic parameters were quantified using Visual 3D (C-Motion, Germantown, MD, USA) after marker data were filtered using a low-pass, Butterworth fourth-order zero-lag filter at a cut-off frequency of 10 Hz which was selected as being the frequency at which 95% of the signal power was below. Kinematic parameters of the hip, knee, and ankle joints were calculated using a Cardan sequence of rotations (*XYZ* or mediolateral–anteroposterior–longitudinal sequence). All data were time-normalized to the stance phase (100%) and processed gait trials were ensemble-averaged. The 3D kinematic measures from the hip, knee, and ankle extracted for statistical analysis were (1) angle at footstrike, (2) range of motion from footstrike to toe-off during stance, (3) peak angle during stance, (4) angular excursion from footstrike to peak angle, and (5) peak angular velocity. These variables were extracted from each of the six trials for each joint in all the three planes of rotation, and the data were then averaged within subjects for statistical analysis.

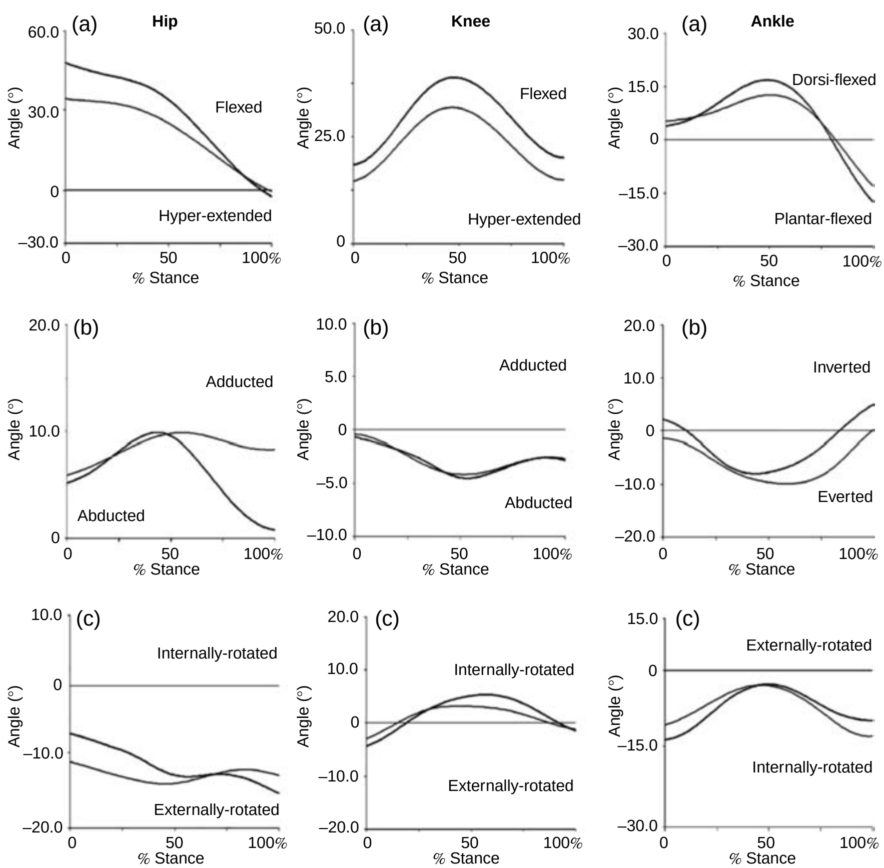

Figure 1. $M \pm SD$ of hip, knee, and ankle joint kinematics in the (a) sagittal, (b) coronal, and (c) transverse planes for overground (black line) and treadmill (grey line) running.

Statistical analysis

To compare differences in 3D kinematic parameters, paired *t*-tests were utilized with an adjusted α level of $p \leq 0.01$ based on the number of comparisons made for each joint in each of the three planes of rotation. The Shapiro–Wilk statistic for each condition confirmed that the data were normally distributed. All statistical procedures were conducted using SPSS 17.0 (SPSS, Inc., Chicago, IL, USA).

Results

The overall patterns of the kinematic curves were qualitatively similar (Figures 1 and 2). Of the 54 observed parameters, 9 exhibited significant ($p \leq 0.01$) differences between treadmill and overground running (Tables I–III). The majority of the significant differences were observed in the sagittal plane. At the hip joint, the overground condition exhibited 12° more hip flexion at footstrike ($p = 0.001$), 17° more hip range of motion ($p = 0.001$), 12.7° more peak flexion ($p = 0.010$), and 8° more transverse plane range of motion ($p = 0.010$). At the knee joint, the overground condition exhibited 5° greater peak knee flexion ($p = 0.010$). At the ankle joint, the overground condition exhibited 6.6° more dorsiflexion excursion from footstrike to peak angle ($p = 0.010$), 191.0°/s greater peak dorsiflexion

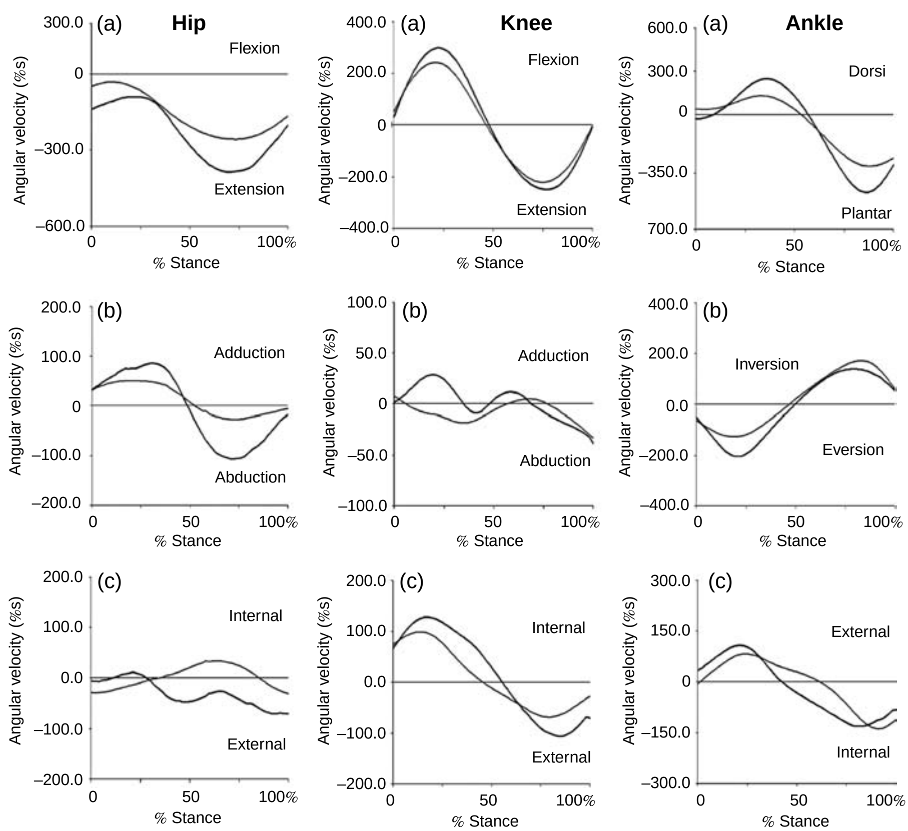

Figure 2. $M \pm SD$ of hip, knee, and ankle joint velocities in the (a) sagittal, (b) coronal, and (c) transverse planes for overground (black line) and treadmill (grey line), running.

Table I. Hip joint kinematics during overground and treadmill running.

	Overground	Treadmill
Sagittal plane		
Angle at footstrike (°)	47.1 ± 13.5	35.1 ± 12.7*
Range of motion (°)	49.6 ± 10.4	32.6 ± 10.5*
Excursion from footstrike to peak angle (°)	2.2 ± 2.7	1.45 ± 2.0
Peak flexion (°)	49.3 ± 8.6	36.6 ± 7.9*
Peak flexion velocity (°/s)	-49.3 ± 70.0	15.0 ± 109.2
Peak extension velocity (°/s)	-399.2 ± 52.3	-288.4 ± 115.7
Coronal plane		
Angle at footstrike (°)	5.7 ± 3.4	6.10 ± 4.5
Range of motion (°)	4.0 ± 5.4	1.0 ± 7.6
Excursion from footstrike to peak angle (°)	5.5 ± 2.8	5.6 ± 7.4
Peak adduction (°)	11.2 ± 3.8	11.7 ± 5.7
Peak adduction velocity (°/s)	139.9 ± 53.2	122.0 ± 34.9
Peak abduction velocity (°/s)	-140.0 ± 64.2	-99.7 ± 50.9
Transverse plane		
Angle at footstrike (°)	-5.7 ± 15.3	-11.3 ± 11.7
Range of motion (°)	8.4 ± 5.4	0.4 ± 13.5*
Excursion from footstrike to peak angle (°)	10.3 ± 4.9	8.9 ± 6.8
Peak external rotation (°)	-16.0 ± 16.5	-20.1 ± 13.7
Peak internal rotation velocity (°/s)	77.5 ± 80.0	93.2 ± 83.4
Peak external rotation velocity (°/s)	-139.7 ± 50.9	-45.5 ± 77.0

Notes: Orientation angles (±): sagittal plane (flexion/extension); coronal plane (adduction/abduction); transverse plane (internal/external rotation). *Significantly different from the overground condition ($p \leq 0.01$).

Table II. Knee joint kinematics during overground and treadmill running.

	Overground	Treadmill
Sagittal plane		
Angle at footstrike (°)	18.0 ± 7.0	19.1 ± 6.3
Range of motion (°)	1.1 ± 8.7	2.1 ± 8.1
Excursion from footstrike to peak angle (°)	21.5 ± 7.5	15.4 ± 6.2
Peak flexion (°)	39.5 ± 5.2	34.5 ± 5.7*
Peak flexion velocity (°/s)	318.3 ± 87.0	276.3 ± 96.0
Peak extension velocity (°/s)	-273.9 ± 72.9	-241.8 ± 116.3
Coronal plane		
Angle at footstrike (°)	-0.4 ± 3.6	1.7 ± 5.6
Range of motion (°)	2.1 ± 8.1	3.5 ± 4.6
Excursion from footstrike to peak angle (°)	5.00 ± 2.7	4.6 ± 4.2
Peak adduction (°)	-5.4 ± 5.4	-2.7 ± 9.00
Peak adduction velocity (°/s)	77.4 ± 31.6	72.7 ± 44.6
Peak abduction velocity (°/s)	-73.0 ± 34.5	-87.4 ± 53.6
Transverse plane		
Angle at footstrike (°)	-4.5 ± 7.2	-3.6 ± 7.8
Range of motion (°)	3.2 ± 4.0	3.2 ± 9.9
Excursion from footstrike to peak angle (°)	11.2 ± 5.0	10.0 ± 7.0
Peak external rotation (°)	6.6 ± 6.0	6.4 ± 8.0
Peak internal rotation velocity (°/s)	166.6 ± 61.4	145.3 ± 58.8
Peak external rotation velocity (°/s)	-160.9 ± 80.4	-108.8 ± 89.5

Notes: Orientation angles (±): sagittal plane (flexion/extension); coronal plane (adduction/abduction); transverse plane (internal/external rotation). *Significantly different from the overground condition ($p \leq 0.01$).

Table III. Ankle joint kinematics during overground and treadmill running.

	Overground	Treadmill
Sagittal plane		
Angle at footstrike (°)	0.6 ± 8.8	4.9 ± 4.0
Range of motion (°)	17.6 ± 10.5	15.1 ± 6.3
Excursion from footstrike to peak angle (°)	17.6 ± 7.9	11.1 ± 4.3*
Peak dorsiflexion (°)	18.2 ± 3.8	16.0 ± 5.7
Peak dorsiflexion velocity (°/s)	575.5 ± 129.0	384.5 ± 145.2*
Peak plantar flexion velocity (°/s)	-286.6 ± 50.2	-185.5 ± 66.6*
Coronal plane		
Angle at footstrike (°)	2.0 ± 5.2	-4.5 ± 10.1
Range of motion (°)	3.2 ± 5.0	4.0 ± 8.0
Excursion from footstrike to peak angle (°)	11.2 ± 4.6	11.0 ± 6.4
Peak eversion (°)	-9.2 ± 7.8	-15.5 ± 8.9*
Peak inversion velocity (°/s)	161.4 ± 480.0	196.6 ± 120.6
Peak eversion velocity (°/s)	-215.2 ± 61.8	-177.4 ± 144.4
Transverse plane		
Angle at footstrike (°)	-13.5 ± 5.1	-9.6 ± 4.9
Range of motion (°)	3.2 ± 3.5	0.7 ± 11.2
Excursion from footstrike to peak angle (°)	10.9 ± 3.5	8.5 ± 4.1
Peak external rotation (°)	-2.7 ± 4.3	-1.1 ± 3.0
Peak external rotation velocity (°/s)	209.7 ± 89.4	210.6 ± 146.9
Peak internal rotation velocity (°/s)	-155.4 ± 89.8	-136.6 ± 48.8

Notes: Orientation angles (±): sagittal plane (dorsi/plantar flexion); coronal plane (inversion/eversion); transverse plane (external/internal rotation). *Significantly different from the overground condition ($p \leq 0.01$).

velocity ($p < 0.001$), and 101.1°/s greater plantar flexion velocity ($p = 0.001$); whereas the treadmill condition was associated with 6.3° more peak eversion ($p = 0.006$).

Discussion and implications

It has been proposed that the mechanics of treadmill locomotion are similar to overground, provided that velocity remains constant (Van Ingen Schenau, 1980). However, in this study, significant differences between overground and treadmill running were found for sagittal plane hip rotation. Overground running was associated with increased peak hip flexion and flexion angle at footstrike. This concurs with the findings of Schache et al. (2001) who observed similar increases in hip flexion during overground running. Overground running in this experiment was also associated with an increased range of motion in hip flexion–extension, which was a product of increased hip flexion at footstrike. This finding is in agreement with previous research (Frishberg, 1983; Gamble et al., 1988; Schache et al., 2001). These findings may be attributable to the reduced stride lengths that have been observed previously during treadmill running (Wank, Frick & Schmidtbleicher, 1998).

The results of this study oppose the findings of the walking protocol conducted by Alton et al. (1998) who observed greater hip flexion and range of motion during treadmill locomotion. Alton et al. (1998) hypothesized that participants utilized these mechanics as a means of avoiding falling off the back of the treadmill and/or keeping up with the belt speed. This was not observed in this study despite moving at a greater velocity, as fear of falling and pressure to maintain a stipulated speed would theoretically be amplified by an increased belt velocity. It is also probable that the length of the treadmill utilized during this investigation (1.0 m longer than that reported by Alton et al., 1998) decreased participants concern that they might fall off the treadmill. Future investigations may wish to assess subjective feedback from participants in order to determine the underlying mechanisms behind gait alterations.

The significant increase in transverse plane range of motion contradicts both the results of Schache et al. (2001) and Fellin et al. (2010a) who found no differences in transverse plane hip joint angular kinematics between overground and treadmill locomotion. Furthermore, the transverse plane hip rotation curve appears in contrast to the previous research investigating running kinematics, in that participants exhibited external rotation at footstrike and continued externally rotating throughout stance. It is hypothesized that this is attributable to the predominantly male sample utilized in the current investigation, as males have been shown to exhibit greater active hip external rotation than females (Ferber, Davis & Williams, 2003).

The increase in peak knee flexion during overground running may relate to the lack of horizontal centre-of-mass (COM) movement documented during treadmill running (Millet et al., 2009; Winter, 1978). As the COM moves over the stance limb, the proximal end of the tibia must move forwards, facilitating an increase in knee flexion. Given that the foot is fixed during the majority of the stance phase, forward motion of the COM forces the tibia to move over the ankle joint creating the dorsiflexion range of motion and also facilitating the increases in dorsiflexion velocity. This finding may also relate to differences in surface hardness between the two conditions. The increase in dorsiflexion range of motion and peak dorsiflexion velocity in conjunction with peak knee flexion may act as a deceleration mechanism which serves to reduce loading of the lower extremity structures (Bobbert, Yeadon & Nigg, 1992). The significant increase in peak plantar flexion velocity during overground running may also relate to COM progression, as plantar flexion velocity plays a key role in the acceleration of the stance limb during the propulsion phase (Adelaar, 1986). Given that the COM is not likely to progress to the same extent between strides in the treadmill condition, the propulsive phase is likely to be less extensive; thus, the extent of the required plantar flexion velocity is reduced.

Observation of the statistical data and kinematic curves of the knee joint in the coronal plane suggests that the knee moves into further abduction after footstrike (Figures 1 and 2). This is perhaps surprising given the predominantly male sample (Malinzak, Colby, Kirkendall, Yu & Garrett 2001) and opposes the movement patterns of Fellin et al. (2010a) and Riley et al. (2008). Fellin et al. (2010a) utilized a functional method of defining hip joint centre, whereas Riley et al. (2008) used a plug-in-gait model which are in contrast to the current investigation. It is proposed that these variations may relate to different methods of estimating the hip joint centre, as coronal plane knee kinematics are sensitive to the method used to locate the hip joint (Stagni, Leardini, Capozzo, Grazia Bendetti, & Cappello, 2000). A number of techniques currently exist which may include radiographic (Bell, Pedersen & Brand, 1990), anatomical (Bell et al., 1989), functional (Cappozzo, 1984; Leardini et al., 1999), and projection (Weinhandl & O'Connor, 2010) methods, all of which may influence the resultant knee position (Stagni et al., 2000). Although the validity of each method has been reported to justify their utilization, there is currently a lack of consensus regarding the most appropriate technique for running analyses which future research may wish to address.

The significant increase in eversion magnitude is in contrast to the observations of both Fellin et al. (2010a) who reported no differences in rearfoot eversion between treadmill and overground running and Riley et al. (2008) who found overground running was associated with significantly greater peak eversion. This finding may relate to the deformation characteristics of the surface during the treadmill condition and has potential clinical significance. Running on treadmills with similar surface characteristics to that utilized in the current investigation may place runners at a greater risk from overuse syndromes such as tibial stress syndrome, plantar fasciitis, and anterior knee pain (Duffey, Martin, Cannon, Craven & Messier, 2000; Lee, Hertel & Lee, 2010; Taunton, Clement & McNicol, 1982; Willems et al., 2006). Therefore, it is recommended that runners utilizing treadmills with similar belt characteristics to this study wear footwear with additional medial stability properties, aimed at reducing rearfoot eversion. Future work may wish to address the influence that different treadmills and belt properties may have on the mechanics of running.

A number of previous investigations examining the mechanics of treadmill and overground locomotion attribute the differences between the two conditions to a lack of familiarization to the treadmill protocol (Wall & Charteris, 1981). Matsas et al. (2000) proposed that significant differences observed between the two conditions are due to a lack of subject familiarization to treadmill locomotion, and concluded that differences may disappear following an appropriate accommodation period. The results of this study appear to oppose this claim as a number of significant differences were observed despite the utilization of a 5-min accommodation period. Matsas et al. (2000) found that reliable kinematic measurements could be obtained following 4 min of treadmill habituation, therefore findings of this investigation appear to be a representative, although it should be noted that the accommodation period was followed by a period of cessation prior to data collection. They also examined the familiarization to treadmill walking and found that its generalizability to running analyses is limited. Future work may wish to determine the most appropriate duration for familiarization to treadmill running.

Limitations

The means by which footstrike and toe-off were determined differed from conventional methods as the treadmill did not feature an integrated force platform. Given this limitation, the stance and swing phases were separated using kinematic data using the Dingwell et al. (2001) method. A number of methods have been utilized for the determination of gait events using kinematic data (Alton et al., 1998; Hreljac & Stergiou, 2000; O'Connor, Thorpe, O'Mally & Vaughan, 2003; Schache et al., 2001; Zeni Richards & Higginson, 2008). However, although these computational methods are repeatable they are known to be associated with error when contrasted to the gold-standard method using force platform data (Fellin, Rose, Royer & Davis, 2010b; Sinclair, Edmundson, Brooks & Hobbs, 2011).

That this investigation utilized a habituation protocol whereby the treadmill was halted then restarted may also serve as a limitation, as participants had limited re-habituation time prior to the commencement of data collection. This may have been inadequate, given that Fellin et al. (2010a) and Riley et al. (2008) utilized habituation protocols of several minutes. Also, the manner in which the statistical analyses controlled for type I error may also be a limitation to this study. This study employed a minimal adjustment for type I error which is in contrast to the more stringent Bonferroni correction adopted by Riley et al. (2008) and may have created a bias towards statistical significance.

A further limitation is that this study observed right foot contact only. Bilateral studies are considered to be more appropriate as symmetry between limbs is unlikely (Cavanagh & Lafortune, 1980). Another prospective constraint of this investigation is that the results are specific exclusively to the treadmill and surface conditions as well as the velocity of motion, and variations in these parameters would likely cause changes in the runners movement strategy. Additional work should therefore be conducted examining the effect of different treadmills on gait mechanics.

Conclusion

This study aimed to compare overground and treadmill running. The 3D kinematics of the lower extremities from the stance phase were observed during overground running and contrasted against the corresponding data from the treadmill. Key parameters of hip flexion at footstrike and ankle excursion to peak angle were found to be significantly reduced during treadmill running, respectively. Treadmill running was found to be associated with significantly greater peak ankle eversion. The results of this study suggest that the 3D kinematics of treadmill running differ significantly in comparison with overground. Therefore, the treadmill should be utilized with caution within clinical and research settings in terms of its ability to mimic stance phase kinematics of overground running.

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