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ABSTRACT

Studies investigating the mechanics of human movement are often conducted using the treadmill. The treadmill is an attractive device for the analysis of human locomotion. Studies comparing overground and treadmill running have analyzed discrete variables, however differences in excursion from footstrike to peak angle and range of motion during stance have yet to be examined. This study aimed to examine the 3-D kinematics of the lower extremities during overground and treadmill locomotion to determine the extent to which the two modalities differ. Twelve participants ran at 4.0m/s in both treadmill and overground conditions. 3-D angular kinematic parameters during the stance phase were collected using an eight camera motion analysis system. Hip, knee and ankle joint kinematics were quantified in the sagittal, coronal and transverse planes, then compared using paired t-tests. Of the parameters analyzed hip flexion at footstrike 12° hip range of motion 17°, peak hip flexion 12.7°, hip transverse plane range of motion 8° peak knee flexion 5° and peak ankle excursion range 6.6°, coronal plane ankle angle at toe-off 6.5° and peak ankle eversion 6.3° were found to be significantly different. These results lead to the conclusion that the mechanics of treadmill locomotion cannot be generalized to overground.

INTRODUCTION

A number of studies investigating the mechanics of human movement 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 allows a larger number of steps to be captured and ensures that continuous movement kinematics are obtained. Thus the treadmill may facilitate a more repeatable pattern of movement in comparison to the short discontinuous trials associated with overground analyses (Fellin et al., 2010). Although this is advantageous it must be demonstrated that the treadmill does not alter the mechanics of the examined movements in comparison to overground motion (Brand and Crowninshield, 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 (Nigg et al., 1995, Schache et al., 2001, Fellin et al., 2010, Riley et al 2008 Frishberg, (1983), and Gamble et al., (1988); 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. Alton et al., (1998), Matsas et al., (2000) and Riley PO et al., (2007) found comparable sagittal plane knee kinematics during overground and treadmill locomotion. Strathy et al., (1983) found that knee joint angular kinematics in the coronal and transverse planes did not differ significantly between the two conditions. Alton et al., (1998) and Riley PO et al., (2007) reported significantly greater hip range of motion and flexion angles during treadmill locomotion.

The kinematics of running have also been compared between overground and treadmill locomotion. Frishberg, (1983), Gamble et al., (1988) and Schache et al., (2001) observed that overground running was associated with increased hip flexion at initial contact, whilst Schache et al., (2001) found no alterations in transverse plane hip motion between the two conditions. There is currently a paucity of comprehensive comparisons regarding the 3-D kinematics of the lower extremities during treadmill and overground running during the stance phase. Riley PO et al., (2008) examined the differences in hip, knee and ankle joint kinematics from both treadmill and overground motion. 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., (2010) 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 and excursion from footstrike to peak angle during stance.

The aim of the current investigation was to assess the extent to which the stance phase mechanics of overground and treadmill locomotion are similar during running. Specifically the 3-D angular kinematics of the lower extremity joints were observed during overground running and compared to the corresponding data from the treadmill.

METHOD

Participants

Eleven males and one female who were free from musculoskeletal injury volunteered to take part in this study. Participants were active recreational runners engaging in training at least 3 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. The mean characteristics of the participants were; age 22.5 ± 4.2 years, height 1.71 ± 0.06m and body mass 75.4 ± 8.4 kg. 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 written informed consent.

Procedure

All kinematic data were captured at 250 Hz via an eight camera motion analysis system (Qualisys Medical, Goteburg, Sweden). Two separate camera systems were used to collect each mode of running. Calibration of the Qualysis^{TM} systems was performed before each data collection session. Only calibrations which produced average residuals of less than 0.85 mm for each camera for a 750.5 mm wand length and points above 4000 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 (CAST) technique using a 6 degrees of freedom (DOF) model (Cappozzo et al., 1995). A static trial was conducted with the participant in the anatomical

position (Figure 1) allowing the positions of the anatomical markers to be referenced in relation to the tracking clusters, following which they were removed. Markers used for tracking remained in place for the duration of the treadmill and overground analyses.

Retro-reflective markers were attached to the 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral epicondyle of the femur, greater trochanter of the right leg, iliac crest, anterior superior iliac spines and posterior superior iliac spines with tracking clusters positioned on the shank and thigh. All markers were positioned by the first author. Hip joint centre was determined based on the Bell, et al., (1989) equations via on the positions of the PSIS and ASIS markers. Each rigid cluster comprised four 19mm spherical reflective markers mounted to a thin sheath of lightweight carbon fiber with length to width ratios of 2.05:1 and 1.5:1 for the femur and tibia respectively, in accordance with Cappozzo et al., (1997) recommendations. Participants wore the same footwear throughout Saucony pro grid guide 2 in sizes 6-9.

@@@**Figure 1 near here**@@@

Given that the treadmill did not feature an integrated force platform, heel strike and toe-off events during both treadmill and overground running were determined using kinematic data based on the Dingwell et al., (2001) method. 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 (Sinclair et al., 2012).

Overground

In the overground condition participants ran at 4.0 m/s in one direction across a 22 m long biomechanics laboratory floor (Altrosports 6 mm, Altro Ltd, Letchworth Garden City, Hertfordshire). Running velocity was monitored using infrared timing gates Newtest 300 (Newtest, Oulu Finland); a maximum deviation of ± 5% from the set 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.

Treadmill

A Woodway™ (ELG, Steinackerstrasse D-79576 Weil Rhein-Germany) high power slatted treadmill maintained at a gradient of 0% was used throughout. Participants were given a five minute habitation period, in which participants ran at the determined velocity, following which the treadmill was stopped for 30’s, and participants dismounted the treadmill before mounting the treadmill for data analysis in accordance with the Alton et al., (1998) recommendation. When participants indicated that they were ready to begin, the treadmill was started and the velocity of the belt was gradually increased until the speed matched that of overground locomotion (4.0m/s). Six trials were recorded.

Data Processing

Trials were processed in Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files. Kinematic parameters were quantified using Visual 3-D (C-Motion, Gaithersburg, USA) after marker data was filtered using a low pass Butterworth 4^{th} 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. 3-D kinematics of the hip, knee and ankle joints were calculated using an XYZ cardan sequence of rotations (where X is flexion-extension; Y is ab-adduction and is Z is internal-external rotation). All data were normalized to 100% of the stance phase then processed gait trials were averaged. 3-D kinematic measures from the hip, knee and ankle which were extracted for statistical analysis were 1) angle at footstrike, 2) angle at toe-off, 3) range of motion from footstrike to toe-off during stance, 4) peak angle during stance and 5) peak angular excursion from footstrike to peak angle. These variables were extracted from each of the six trials for each joint in all three planes of rotation and the data was then averaged across participants for statistical analysis. Participants kinematic curves for each joint angle were time normalized to stance were ensemble averaged for visual purposes only.

Statistical analysis

Descriptive statistics (mean ± standard deviation) were calculated for the outcome measures. To compare differences in 3-D kinematic parameters paired t-tests were utilized with an adjusted alpha level of $p=0.01$ 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, USA).

RESULTS

Figure 2 presents mean 3-D angular motions of the hip, knee and ankle during the stance phase of both treadmill and overground running. Tables' 1, 2 and 3 show means, standard deviations and the results of the statistical analysis of the outcome measures.

Of the 45 observed parameters 8 exhibited significant $p \leq 0.01$ differences between overground and treadmill running (tables 1-3). The majority of the kinematic differences between the two modalities were observed in the sagittal plane. At the hip joint overground runners exhibited 12°, p=0.001 more hip flexion at footstrike, 17°, p=0.001 more hip range of motion and 12.7°, p=0.001 more peak flexion than in the treadmill condition and 8°, p=0.01 more transverse plane range of motion. At the knee overground runners were found to be associated with greater peak knee flexion 5°, p=0.01. At the ankle overground runners exhibited 6.5°, p=0.01 more excursion from footstrike to peak angle and 5.7°, p=0.007 more inversion, whereas treadmill runners were associated with 6.3°, p=0.006 more peak eversion.

@@@@@ **Figure 2 near here** @@@@@

@@@@@ **Table 1 near here** @@@@@

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DISCUSSION

The aim of this study was to provide a 3-D kinematic comparison of treadmill and overground running. This study represents the first comparative study specifically concerning the lower extremity 3-D angular range of motion and peak excursion parameters during the stance phase between the two conditions. The results indicate that several kinematic differences were observed between the two running modalities.

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 initial contact. 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 during overground running, as hip flexion at toe-off was found to be similar for the two conditions. This finding agrees with the findings of Frishberg (1983), Gamble et al., (1988) and Schache et al., (2001). These findings may be attributable to the reduced stride lengths that have been observed previously during treadmill running (Wank et al., 1998). Furthermore, it is hypothesized that the slatted treadmill belt may have acted as a visual cue which served to further accentuate this adaptation causing the large difference between the two conditions. Future, research may therefore wish to investigate the influence of both slatted and smooth treadmill belts of the 3-D kinematics of running.

Furthermore, 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. The results of the current investigation appear to oppose this notion in that participants did not exhibit similar patterns, 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 (1.0m 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 contradict the results of Schache et al., (2001) and Fellin et al., (2010) who found no differences in transverse plane hip joint angular kinematics between overground and treadmill locomotion. Furthermore, the transverse plane hip rotation curve appears to contrast 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 et al., 2003).

The increase in peak knee flexion during overground running has not been reported previously. It is proposed that this finding is attributable to the difference in centre of mass progression during overground running as the centre of mass moves over the stance limb the proximal end of the tibia must move forwards, facilitating an increase in knee flexion. Similarly, the significant increase in the angular excursion from footstrike to peak dorsiflexion has not been reported previously within the literature. It is proposed that this is also attributable to the increase in centre of mass progression in the overground condition. Given that the foot is fixed during the majority of the stance phase, forward motion of the centre of mass forces the tibia to move over the ankle joint creating the dorsiflexion range of motion. This finding may also relate to differences in surface hardness between the two conditions. The increase in dorsiflexion range of motion in conjunction with peak knee flexion may act as a deceleration mechanism which serves to reduce loading of the lower extremity structures (Bobbert et al., 1992).

Observation of the statistical data and kinematic curves of the knee joint in the coronal plane suggests that the knee is biased towards abduction for the entire stance phase. This is perhaps surprising given the predominantly male sample (Malinzak et al., 2001), yet this finding does concur with the findings of Ferber et al., (2003) who also observed that male runners were biased towards abduction. Given that knee angular kinematics outside the sagittal plane are sensitive to the method used to predict the hip joint centre (Stagni et al., 2000); it is possible that inter-study variations in knee coronal plane mechanics may relate to the different methods of quantifying the location of the hip joint centre. A number of techniques currently exist which may include radiographic (Bell et al., (1990), anatomical Bell et al., (1989), functional (Cappozzo, 1984; Leardini et al., 1999) and projection (Weinhandl and O'Connor, 2010) based methods, all of which may influence the resultant knee position (Stagni et al., 2000). Although the efficacy and validity of each method have been reported to justify their utilization, there is currently a lack of consensus regarding the most appropriate technique which future research may wish to address.

During during treadmill running, the ankle was found to be slightly more dorsiflexed at footstrike. This finding contrasts the findings of Wank et al., (1998), Fellin et al., (2010) and Nigg et al., (1995), who found decreased ankle dorsiflexion at footstrike. This change in sagittal plane ankle position at foot contact may relate to a change in strike pattern as plantar/dorsi flexion of the ankle is one of the mechanisms by which leg stiffness is regulated (Bishop et al., 2006). It is hypothesized that the reduced stiffness of the treadmill surface may have led to the increased dorsiflexion at footstrike as runners have been found to adjust their leg stiffness in response to differences in surface hardness (Bishop et al., 2006).

The significant increase in eversion magnitude is in contrast to the observations of Fellin et al (2010) who reported no differences in rearfoot eversion parameters between treadmill and overground running. This finding may relate to the deformation characteristics of the surface during the treadmill condition and has potential clinical significance. These findings suggest that running on this type of treadmill may be associated with an increased risk from injury as rearfoot eversion is implicated in the aetiology of a number of overuse injuries (Willems et al., 2004, Lee et al ., 2010, Taunton et al ., 2002 and Duffey et al., 2000). Therefore treadmill runners may be at a greater risk from overuse syndromes such as tibial stress syndrome, plantar fasciitis and anterior knee pain (Willems et al., 2004, Lee et al., 2010, Taunton et al., 2002 and Duffey et al., 2000).

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 and Charteris, 1981). Mastas et al*.*, (2000) proposes studies reporting significant differences between the two conditions locomotion have generally put little emphasis on subject familiarisation 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 five minute accommodation period. Furthermore, the findings of the current investigation appear to be representative and as Matsas et al*.*, (2000) found that reliable kinematic measurements could be obtained following 4 minutes of treadmill habituation.

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*.*, (1998) method. A number of methods have been utilized for the determination of gait events using kinematic data (Alton et al., 1998, Hreljac and

Stergiou., 2001, Zeni et al., 2008, O'Connor et al., 2003 and Schache et al., 2001). 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 et al., 2010 and Sinclair et al., 2011).

A possible 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 and Lafortune, 1980). Another prospective restriction of the current 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.

Conclusions

The results of this study suggest that treadmill should be utilized with caution within clinical and research settings in terms of its ability to mimic the mechanics of overground running. Furthermore, given that injury patterns may to differ between the two conditions it is also recommended that runners consider their primary method of training when selecting the most appropriate footwear for their needs as treadmill runners are likely to require footwear with additional medial stability properties, aimed at reducing rearfoot eversion.

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