Original Research

Differences in Lower Extremity Kinematics Between High School Cross-Country and Young Adult Recreational Runners

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Background

While previous research has assessed running kinematics for age-related differences that could increase the risk of a running-related injury, none of these studies have included high school aged runners or assessed running kinematics using 2-dimensional video analysis.

Purpose

The purpose of this study was to compare sagittal plane kinematics during treadmill running in high school cross-country and young adult recreational runners using 2-dimensional motion analysis techniques.

Methods

Twenty-five high school cross-country runners (13 women, 12 men) and 25 young adult recreational runners (12 women, 13 men) consented to participate in this study. Reflective markers were placed on each lower extremity over multiple anatomical landmarks. After a five-minute acclimation period in which the participants ran on a treadmill at their preferred running speed, video data were recorded at 240 frames per second for all participants while they continued to run on the treadmill.

Results

There were no significant differences between left and right extremities. The young adult recreational runners exhibited significantly greater vertical excursion of the center of mass (t = 4.64, p = .0001) compared to the high school runners. There was no significant difference between the two age groups regarding the six other sagittal plane variables.

Conclusions

The young adult recreational runners demonstrated an increased center-of-mass vertical excursion in comparison to high school cross-country runners. In addition, the results obtained in this study for kinematic variables using 2-dimensional motion analysis were similar to previously reported studies using 3-dimensional motion analysis, demonstrating that 2-dimensional motion analysis could be used for analyzing sagittal plane running kinematics in clinical settings.

Level of Evidence

4, Controlled laboratory study

BACKGROUND

Cross-country running continues to be a popular high school sport in the United States, with 493,613 participants during the 2017-2018 school year.[1] This ranks cross-country as the fifth most popular sport behind football, track & field, basketball, and soccer. Previous studies have reported

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that 29% to 38.5% of these high school cross-country runners will sustain an injury annually, with many of these injuries resulting in a loss of 1 to 7 days of participation.[2-4] The most common injury sites in high school cross-country runners are the leg (medial tibial stress syndrome, stress fractures, and compartment syndrome) and the knee (anterior knee pain).[2,3,5] Most researchers agree that the etiology of running injuries is multifactorial with contributing factors including age, sex, history of previous injury, lower extremity bony alignment, running terrain, and running kinematics.[6-8] While several intrinsic and extrinsic factors, including, age, alignment, and history of previous injury cannot be altered, running kinematics can be modified based on a video analysis of running mechanics. Several running kinematic variables, including the foot inclination angle at initial contact, vertical displacement of the center of mass, and total knee flexion during stance phase have been related to higher peak vertical ground reaction forces, increased peak knee extensor moments, and reduced shock absorption, all of which can increase the stresses placed on the leg and knee during running.[7] As previously noted, the leg and knee are common locations of running-related injuries in high school cross-country runners.

Based on this evidence, it would appear to be advisable that an assessment of running kinematics be incorporated into the care of high school cross-country runners, either as a component of a pre-season screen or as an injury management program during the season. Previous research has demonstrated that 2-dimensional analysis of kinematic sagittal plane motion using a single video camera with an adequate frame rate (greater than 100 frames per sec) is similar to kinematic values obtained with 3-dimensional analysis of sagittal plane motion during running.[9-11] Wille et al. utilized 3-dimensional motion analysis in their study of 45 participants during treadmill running and suggested that 2-dimensional motion analysis would likely be sufficient to capture several kinematic variables during running including center of mass height at midstance and at double-float, the foot inclination angle at initial contact, and peak knee flexion angle.[10] Wille et al. supported this suggestion based on the strong correlations between 2-dimensional and 3-dimensional motion analysis of sagittal plane motion during running.[10] In a more recent study, Schurr et al. reported a high correlation between 2-dimensional and 3-dimensional motion analysis for sagittal plane lower extremity movement.[11] The use of 2-dimensional motion analysis to assess sagittal plane kinematics enhances the ability of sports physical therapists to assess running kinematics in the clinic without the need for expensive equipment and complex analysis software that are required to perform 3-dimensional video-based running gait analyses. However, there is a paucity of published normative kinematic data for high school cross-country runners.

Several researchers have evaluated the effect of aging on running kinematics during both overground and treadmill running.[12-17] However, the range of runners' ages included in these studies was between 20 and 68 years of age. Devita and colleagues compared overground running kinematics and kinetics among four age groups: 20 to 29 years, 30 to 39 years, 40 to 49 years, and 50 to 60 years.[14] The only sagittal plane kinematic variable assessed in their study was the maximum knee flexion angle that occurred during stance phase while running.[14] While the mean maximum knee flexion angle for all groups combined was 39.6°, the mean value for the 20 to 29 year old group (40.6°) was significantly greater than the mean value for the 50 to 59 year old group (36.8°), indicating that maximum knee flexion during stance phase decreases with age. While Devita et al. reported that 110 runners participated in their study, they did not indicate the number of runners in each of the four age groups. When assessing overground running mechanics in two groups of 15 runners with mean ages of 21.2 years and 54.6 years, Silvernail and colleagues reported similar findings in that both maximum knee flexion during stance phase and total knee flexion (the difference between knee flexion at initial contact and maximum knee flexion during stance phase) were decreased in the older group of runners.[16] In a more recent study, Boyer and colleagues reported that when running at matched speeds, the impact of aging on running mechanics is subtle for both men and women.[13] However, these authors found that mature male runners have greater knee flexion in comparison to a group of younger male runners.[13] In an assessment of 18 females (mean age 23.7 years) and 14 males (mean age 25.0 years) during treadmill running, Almonroeder and Benson found no significant difference in the maximum knee flexion angle during stance phase between male and female runners,[12] supporting the conclusion offered by Boyer and colleagues.[13] These findings indicate that there are minimal differences in sagittal plane running mechanics between male and female runners.

Based on the outcomes of these studies, there are mixed results regarding the effect of aging on maximum knee flexion during the stance phase of running. Unfortunately, previous studies have not evaluated the effect of aging on other commonly described sagittal plane kinematic variables other than those that are focused on the knee during running.[17] In addition, none of these studies have included high school aged runners. After an extensive review of the literature, to the best of the authors' knowledge, no study to date has assessed the differences in sagittal plane running kinematics between high school cross-country runners and an older group of runners using 2-dimensional motion analysis. A comparison of 2-dimensional sagittal plane kinematic data between high school runners and an older group of runners would inform clinicians of similarities and differences in running kinematics between these groups. These data could also be used to assess high school cross-country runners who are returning to activity following injury, as well as to better understand differences in running kinematics associated with aging. Thus, the purpose of this study was to compare sagittal plane kinematics during treadmill running in high school cross-country and young adult recreational runners using 2-dimensional motion analysis techniques. Based on the findings from previous studies that have assessed the effect of aging on running kinematics, we hypothesized that maximum knee flexion during stance phase and total knee flexion would be greater in the high school cross-country runners in comparison to the adult recreational runners. For this study, the definition for total knee flexion described by Silvernail et al. was utilized with total knee flexion representing the difference be-

tween knee flexion at initial contact and maximum knee flexion during stance phase.[16]

METHODS

PARTICIPANT CHARACTERISTICS

Twenty-five high school cross-country runners (13 women, 12 men) and 25 young adult recreational runners (12 women, 13 men) voluntarily consented to participate in this study. The mean age of the 25 high school runners was 15.4 years, with a range of 14 to 17 years. The mean age of the 25 young adult recreational runners was 28.2 years, with a range of 24 to 39 years. A sample of convenience was utilized based on a 3-month period of subject recruitment and excluded those athletes who did not meet the inclusion criteria. Participants were recruited from running clubs and local area high schools through community advertisements and public information sessions. All participants selected for this study met the following inclusion criteria: (1) were between the ages of 14 and 40 years; (2) ran, on average, at least 18 miles per week for no less than one year prior to participation in the study; (3) had experience running on a treadmill; and (4) had no previous history of a lower extremity congenital or traumatic deformity or previous surgery that resulted in altered bony alignment. Any participant who had an acute injury three months prior to participation in the study that led to the inability to run for at least three consecutive days was excluded from participating the study. The inclusion and exclusion criteria for this study were based on criteria used in several previous studies assessing running kinematics.[10,12,14,18] The Regis University Institutional Review Board approved the study protocol, and all participants provided written informed consent. In addition, a separate parental consent was obtained for all participants under the age of 18 years prior to participating in the study.

DATA ACQUISITION

Upon arrival at the testing center, each participant's height, weight, and blood pressure were recorded. Next, participants were asked to begin shod running on a treadmill (Model Mercury S, Woodway USA Inc., Waukesha, WI 53186) for at least 5 minutes in order to acclimate to the treadmill as well as to determine their preferred running speed for testing. Once the preferred running speed was selected and the participant indicated that they were acclimated to the treadmill, 9 mm spherical reflective markers were placed on each lower extremity over the following locations: anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), lateral epicondyle of the femur, lateral malleolus, lower posterior calf above the Achilles tendon (two markers), and midline of the heel (two markers). To minimize ASIS and PSIS marker movement, elastic self-adhesive wrapping was applied around each participant's waist prior to marker placement. The reflective marker placements used in this study were previously evaluated by Reinking et al., who reported high levels of intra-rater and inter-rater reliability when using these marker placements while performing a 2-dimensional sagittal plane motion analysis during running.[18]

Once all markers were in place, the participant was asked to start running on the treadmill at their pre-selected running speed. When the participant indicated that they were in their typical running pattern, they continued to run at their preferred speed for a minimum of five minutes. After running for four minutes at their preferred running speed, video data were recorded for the right and left sagittal plane (side view) for 60 sec. All running motion data were recorded using a single high-speed camera (Model# EX FH25, Casio America Inc., Dover, NJ 07801) at 240 frames per second. The lens of the high-speed camera was positioned at a 90-degree angle and at a distance of 2 m from the center of the treadmill for all video recordings based on previous research that assessed 2-dimensional motion analysis during treadmill running.[18]

DATA ANALYSIS

The left and right sagittal plane video clips for each runner were assessed by a single rater (TGM) who has over 12 years of experience performing 2-dimensional video-based running analyses on both collegiate and recreational runners. The rater selected a stride for analysis after the third foot strike on the video clip to observe the runner's gait pattern and enhance the rater's ability to identify initial foot contact. The following seven sagittal plane (side view) kinematic variables were assessed on both the left and right lower extremities for all runners: 1) angle of shoe to treadmill at initial contact (SHOE_Ang), 2) angle of leg to vertical at initial contact (LEG_Ang), 3) knee flexion at initial contact (KN_FL_IC), 4) maximum knee flexion at midstance (Max_KN_FL), 5) distance of the vertical line from the estimated center of mass (center of the line connecting ASIS and PSIS) to the posterior aspect of the shoe (COM_To_Shoe), 6) vertical position of the estimated center of mass at midstance, and 7) highest vertical position of the estimated center of mass during double float phase. KN_FL_IC was subtracted from Max_KN_FL to calculate total knee flexion (KN_FL_Tot). The vertical position of the estimated center of mass at double float was subtracted from the vertical position of the estimated center of mass at midstance to calculate the vertical excursion of the center of mass (COM_Vt_Ex). The seven kinematic variables selected for analysis in this study have been previously identified as important sagittal plane variables that should be included in an analysis of running mechanics.[7] In addition, all seven kinematic variables have been shown to have high levels of within and between rater reliability for both inexperienced and experienced raters.[18] All angles were measured in degrees and all distance measurements were recorded in centimeters using a free-access video analysis software program (Kinovea, version 0.8.15, http://www.kinovea.org). Puig-Divi et al. have reported that the Kinovea software is a valid and reliable tool to assess kinematics at distances up to 5 m from the object and at an angle of 90 degrees.[19]

In a previously published study, the rater in this study (TGM) demonstrated intra-rater levels of reliability between 0.75 and 0.98 (ICC) and inter-rater reliability values between 0.76 and 0.97 (ICC) for all kinematic variables assessed in the current study in comparison to another rater with a similar level of experience.[18] The rater was blinded

Table 1: Participant Demographics

	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m^2)	Treadmill Running Speed (m/s)
High School Runners (n=25)	15.4 ± 1.3	168.7 ± 9.4	55.3 ± 9.2	19.4 ± 0.8	3.0 ± 0.4
Young Adult Recreational Runners (n=25)	28.2 ± 4.1	172.9 ± 9.7	67.8 ± 10.3	22.7 ± 2.4	3.0 ± 0.3

Table 2: Running kinematic variables (mean ± standard deviation) for the high school cross country and young adult recreational runners.

VARIABLE	High School Cross-Country Runners			Young Adult Recreational Runners		
	Left (n=25)	Right (n=25)	Combined (n=50)	Left (n=25)	Right (n=25)	Combined (n=50)
Angle of shoe at initial contact (SHOE_Ang) – *in degrees*	7.76 ± 10.72	7.08 ± 11.25	7.42 ± 10.88	11.00 ± 7.23	10.36 ± 7.53	10.68 ± 7.31
Angle of leg at initial contact (LEG_Ang) - *in degrees*	8.20 ± 2.35	6.80 ± 3.38	7.50 ± 2.96	7.04 ± 2.44	5.76 ± 2.83	6.40 ± 2.70
Distance of center of mass to posterior aspect of shoe (COM_To_Shoe) – *in cm*	16.44 ± 3.73	15.09 ± 3.30	15.77 ± 3.55	15.75 ± 3.19	14.60 ± 3.54	15.18 ± 3.38
Knee flexion at initial contact (KN_FL_IC) – *in degrees*	11.20 ± 3.99	10.24 ± 5.25	10.72 ± 4.64	11.52 ± 4.16	11.04 ± 4.20	11.28 ± 4.15
Maximum knee flexion during stance phase (Max_KN_FL) – *in degrees*	38.80 ± 4.53	39.32 ± 4.50	39.06 ± 4.47	41.20 ± 3.88	41.36 ± 4.06	41.28 ± 3.93
Total knee flexion (Kn_FL_Tot) – *in degrees*	27.60 ± 3.99	29.08 ± 6.01	28.34 ± 5.11	29.60 ± 3.96	30.28 ± 4.92	29.94 ± 4.43
Total vertical excursion of center of mass (COM_VtEx) – *in cm*	6.38 ± 1.54	6.51 ± 1.64	6.45 ± 1.57*	7.60 ± 1.60	8.33 ± 1.74	7.96 ± 1.70*

* p = .0001

while performing the video analyses on all runners.

STATISTICAL ANALYSIS

In addition to descriptive statistics, t-tests were performed to determine if there were significant differences between left and right extremities and between the high school cross-country and young adult recreational runners for all seven kinematic variables. The seven variables included SHOE_Ang, LEG_Ang, KN_FL_IC, COM_To_Shoe, Max_KN_FL, KN_FL_Tot, and COM_Vt_Ex. All statistical analyses were performed using JMP software, Version 8 (SAS Institute Inc., Cary NC 27513). Because of the multiple number of t-tests performed, the Holm-Bonferroni method was used to determine an alpha level of 0.001 for all tests of significance.[20]

RESULTS

Participant demographics are listed in Table 1, and descriptive statistics for all seven kinematic variables are listed in Table 2. The mean (standard deviation) running speed for the high school runners was 3.0 (± 0.4) m/s and was 3.0 (± 0.3) m/s for the adult recreational runners. There was no significant difference in the running speed between the two groups (t = 0.00; df = 48; p = 1.00). A forefoot or midfoot strike pattern was noted for seven of the high school runners and four of the young adult recreational runners, with all other runners using a rearfoot strike pattern. The results of the t-tests indicated that mean values between the left and right extremities for the 25 high school and 25 young adult recreational runners for all seven kinematic variables were not significantly different. Based on these results, data for the left and right extremities were grouped for the high school runners (n=50) and the young adult recreational runners (n=50) for all further analyses. The only significant result of the t-tests on the seven kinematic variables between the high school and young adult recreational runners was COM_Vt_Ex (t = 4.61; df = 98; p = .00001). The mean value for COM_Vt_Ex for the young adult recreational runners was 1.51 cm greater than the mean value for the high school runners. None of the other six kinematic variables were significantly different between the high school cross-country and young adult recreational runners.

DISCUSSION

Knowledge of sagittal plane kinematic variables during running, including foot inclination angle at initial contact, vertical displacement of the center of mass, and maximum knee flexion during stance phase can aid the clinician in understanding the magnitude of ground reaction forces.[7,10] High ground reaction forces have been shown to contribute to increased stress on the leg and knee during running.[21,22] This is important information for the sports physical therapist since epidemiological studies have shown that the leg and knee are common locations of running-related injuries in high school cross-country runners.[2,3,5] In addition, running kinematic data for sagittal plane motion would provide the clinician with normative kinematic values to utilize when assessing high school cross-country runners who are returning to activity following a running-related injury or as part of a pre-season screening examination. In addition, assessing running kinematics for high school runners in comparison to an older group of runners would enhance the understanding of the effect of aging on running kinematics. Thus, the intent of this study was to compare sagittal plane kinematics during treadmill running in high school cross-country and young adult recreational runners using 2-dimensional motion analysis techniques.

Based on the findings of previous studies comparing different age groups of runners, the authors of this study hypothesized that Max_KN_FL and total knee flexion would be significantly greater in the high school cross-country runners in comparison to the young adult recreational runners. The t-test results on the seven sagittal plane running variables that were assessed in this study found that only COM_Vt_Ex was significantly different between the high school cross-country runners and the young adult recreational runners. The mean difference in the COM_Vt_Ex between the two groups of runners was 1.51 cm, with a mean value of 6.45 cm for the high school runners and 7.96 cm for the young adult recreational runners. Based on these findings, the authors rejected their initial hypothesis. The 1.51 cm difference in the COM_Vt_Ex reveals that the high school runners assessed in the current study were more efficient in attenuating ground reaction forces during treadmill running than the adult recreational runners.

As noted in the review of the literature, previous studies assessing differences in running mechanics secondary to aging have focused on the kinematic variables of maximum knee flexion during stance phase and total knee flexion.[12–14,16] While not significantly different between the two groups of runners in the current study, the mean values for Max_KN_FL was 39.06° for the high school runners and 41.28° for the young adult recreational runners. These mean values are comparable to the values reported in previous studies that have studied the effect of aging on running mechanics. The mean value for Max_KN_FL reported by Silvernail et al. was 39.17° for younger runners (mean age 21.1 years) and 38.06° for an older group of runners (mean age 54.6 years).[16] Devita et al. reported that Max_KN_FL was 42.1° for a group of runners between the ages of 20 and 29 years and 39.8° for runners between the ages of 30 and 39 years.[14] Silvernail et al. also reported that the mean total knee flexion for younger runners was 28.40°.[16] This value

is comparable to the mean total knee flexion obtained in the current study for the high school cross-country runners (28.34°). The similarity of the mean values for Max_KN_FL between the current study and the findings reported by Silvernail et al.[16] and Devita et al.[14] is remarkable in light of the fact that both Silvernail et al. and Devita et al. used 3-dimensional motion analysis in their studies. This would suggest that the data obtained using 2-dimensional motion analysis techniques to assess angular values in the sagittal plane during running are similar to the values obtained using 3-dimensional motion analysis techniques.[10,11] In the current study, 2-dimensional motion analysis using a single, low-cost, high-speed camera to record sagittal plane running motion was utilized, as well as a free-access video analysis software program, in order to enhance the clinical applicability of the findings. Further research is required, however, to determine if sagittal plane kinematic variables assessed using 2-dimensional and 3-dimensional motion analyses are comparable.

In the current study, the mean value for Max_KN_FL was greater for the young adult recreational runners in comparison to the younger high school cross-country runners. Findings of recent studies indicate that older runners had greater knee flexion as compared to a group of younger runners.[13,23] The findings of the current study agree with those by Boyer et al.[13] and Jin and Hahn[23] and further support the need for additional research to assess the differences in knee range of motion between different age groups of runners. As described earlier, previous studies have not evaluated the effect of aging on commonly described sagittal plane kinematic variables except for those that are focused on the knee during running.[15] Thus, further comparisons of other sagittal plane running kinematic variables assessed in this study cannot be made.

A limitation in the current study was the use of a treadmill to assess both kinetic and kinematic variables during running. Several studies have reported on the validity of using a treadmill for running analysis, with the major concern being the alteration of the runner's pattern of lower extremity movement as well as ground reaction forces. In one of the only studies to compare overground and treadmill running kinematics and kinetics using a force-transducer instrumented treadmill, Riley et al. reported that a treadmill-based analysis of running mechanics can be generalized to overground running mechanics, provided that the running speed on the treadmill is similar to the individual's overground running speed.[24]

Another limitation is that only 25 runners were assessed in each of the groups in the current study. However, it is important to note that these participant numbers are comparable to the number of runners utilized in previous studies assessing the effect of aging on running mechanics. While the assessment of the video clips for each runner by a single rater could also be viewed as a limitation of the study, the rater used in this study had previously demonstrated high levels of intra-rater and inter-rater reliability for all kinematic variables assessed in the current study in comparison to another rater with a similar level of experience.[18] Although this study provides the clinician with preliminary normative values of selected sagittal plane variables that can be used when performing a 2-dimensional treadmill

motion analysis of high school cross-country runners, further investigations are required to provide more robust sagittal plane kinematic normative values for the assessment of high school cross-country runners.

CONCLUSION

To the best of the authors' knowledge, this is one of the first studies to assess differences in sagittal plane kinematics between high school cross-country and young adult recreational runners during treadmill running. The results of the current study suggest that the high school runners assessed in the current study were slightly more efficient in attenuating ground reaction forces by decreasing the COM_Vt_Ex during treadmill running. Additionally, the results obtained in this study for Max_KN_FL and total knee flexion using 2-dimensional motion analysis are similar to values previously reported studies using 3-dimensional motion analysis. The use of 2-dimensional motion analysis as well as a free-access video analysis software program in the current study enhances the feasibility of the sports physical therapist to assess these variables in high school cross-country runners in a typical clinical setting. Further research is required to determine if sagittal plane kinematic variables assessed in the current study are comparable irrespective of whether 2-dimensional or 3-dimensional motion analysis techniques are used, as well as to provide more robust normative kinematic values for high school cross-country runners.

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