IJSPT
INTERNATIONAL JOURNAL OF SPORTS PHYSICAL THERAPY

Martinez C, Garbett S, Hiromasa K, et al. Comparison of 2-D and 3-D Analysis of Running Kinematics and Actual Versus Predicted Running Kinetics. *IJSPT*. 2022;17(4):566-573. doi:10.26603/001c.34432

Original Research

Comparison of 2-D and 3-D Analysis of Running Kinematics and Actual Versus Predicted Running Kinetics

Caitlyn Martinez, PT, DPT[1], Seth Garbett, PT, DPT[1], Kristen Hiromasa, PT, DPT[1], Rhandi Jackson, PT, DPT[1], Eric Miya, PT, DPT[1], Michelle Miya, PT, DPT[1], Joshua D White, PT, DHSc, ATC[1], Brian S Baum, PhD[2], Mark F Reinking, PT, PhD, SCS, ATC, FAPTA[1][a]

[1] School of Physical Therapy, Regis University, [2] Lincoln Laboratory, Massachusetts Institute of Technology

Keywords: Gait analysis, loading rate, running assessment

https://doi.org/10.26603/001c.34432

International Journal of Sports Physical Therapy
Vol. 17, Issue 4, 2022

Background

Providing clinicians with an accurate method to predict kinetic measurements using 2D kinematic motion analysis is crucial to the management of distance runners. Evidence is needed to compare the accuracy of 2D and 3D kinematic measurements as well as measured and estimated kinetic variables.

Purposes

The objectives of this study were to (1) compare 2D video analysis of running kinematics with gold standard 3D motion capture and, (2) to evaluate published equations which estimate running kinetics using 2D kinematic and spatiotemporal values and modify these equations based on study findings.

Design

Controlled laboratory study, cross-sectional design

Methods

Runners who averaged at least 20 miles per week were invited to participate. Athletes ran on an instrumented treadmill at their preferred training pace for a 6-minute warm-up. Markers were placed over designated anatomical landmarks on both sides of the pelvis as well as the left lower extremity. Subjects then ran at their preferred speed and kinematic data were recorded using both the 2D and 3D camera systems at 240 frames/second. Additionally, ground reaction forces were recorded at 1200Hz. 2D and 3D kinematic values were compared and published kinetic prediction formulas were tested. Linear regression was used to develop new prediction equations for average loading rate (AVG_LR), peak vertical ground reaction force (VERT_GRF), and peak braking force (PK_BRK). Paired t-tests were used to assess differences between the 2D and 3D kinematic variables and the measured (MEAS) and calculated (CALC) kinetic variables.

Results

Thirty runners (13 men and 17 women) voluntarily consented to participate in this study and the mean age of the participants was 31.8 years (range 20 to 48 years). Although significant differences existed, all 2D kinematic measures were within 2°-5° of 3D kinematic measures. Published prediction equations for AVG_LR and VERT_GRF were

---

[a] **Corresponding author:**
Mark F. Reinking
Regis University
School of Physical Therapy
3333 Regis Blvd. G-4
Denver, CO 80221
mreinking@regis.edu

supported, but new prediction equations showed higher R^2 for AVG_LR (0.52) and VERT_GRF (0.75) compared to previous work. A new prediction equation for PK_BRK was developed. No significant differences were found between the MEAS and CALC kinetic variables using the new equations.

Conclusion

Accurate predictions of kinetic variables can be made using spatiotemporal and 2D kinematic variables.

Level of Evidence

Level 2

INTRODUCTION

Running is one of the most popular fitness activities across the world. In the United States, over 55 million individuals participate in running.[1] While it is one of the most efficient ways for adults to achieve physical fitness,[2] the incidence of injuries associated with running is relatively high.[2] Injuries can diminish pleasure in running as a physical activity as well as contribute to medical costs and possible impact on physical fitness. Commonly reported running-related injuries (RRI) include stress fractures, medial tibial stress syndrome, patellofemoral pain, Achilles tendinopathy, iliotibial band syndrome, and plantar fasciitis.[3-7] The etiology of RRI is clearly multifactorial involving runner characteristics (age, sex, nutrition), training variables (weekly mileage, training surfaces, abrupt changes in training), and biomechanical variables. The biomechanical variables that have been associated with RRI risk include kinematic variables (joint position, velocity, and acceleration), kinetic variables (force, loading rate), and temporospatial variables (cadence, stride length).[8]

Davis et al[9] conducted a prospective study of female runners comparing kinetic variables in a never-injured group and an injured group. They found that all impact-related kinetic variables (vertical instantaneous loading rate, vertical average loading rate, vertical impact peak, and peak vertical force) were significantly higher in the injured group compared to those who have never been injured. Earlier studies have also shown that higher vertical forces may contribute to running-related injuries.[9-14] Peak braking force[15] and braking impulse[16-18] have also been shown to be significant predictors of RRI .

In well-equipped biomechanical laboratories, researchers collect kinematic and kinetic data using sophisticated 3-D motion capture systems and in-ground force plates or instrumented treadmills. However, many clinicians working in outpatient settings do not have access to such equipment. They can, however, use 2D digital video cameras to reliably collect kinematic data of runners.[19] Wille et al[20] conducted a study using 2D video analysis of a group of 45 runners and concluded that it is possible to estimate kinetic data using sagittal plane kinematics and temporospatial variables. In an earlier study,[21] the researchers used cadence and sagittal plane kinematics collected with a 2D high speed camera to develop a prediction equation to estimate kinetic variables in high school cross country runners. Using five sagittal-plane kinematic variables (shoe angle, leg angle, knee flexion at initial contact, total knee motion, and total vertical excursion of center of mass) and cadence, 56% of the vertical ground reaction force variance and 51% of the average loading rate variance was explained. To confirm the feasibility and improve accuracy of these estimates, further evidence is needed in the comparison of 2D and 3D kinematic measurements as well as the comparison of measured and estimated kinetic variables. The objectives of this study were (1) to compare 2D video analysis of running kinematics captured with a high-speed video camera with gold standard 3D motion capture and, (2) to evaluate equations which estimated running kinetics using 2D kinematics and spatiotemporal values and modify these equations based on study findings. The two research hypotheses were (1) 2D kinematics would not differ from 3D kinematic variables, and (2) newly developed equations would improve the accuracy of estimated kinetic variables.

METHODS

This cross-sectional study was conducted at the Regis University biomechanics research lab from August through November 2019. We utilized a sample of convenience; participants were recruited from flyers posted around Regis University campus and e-mails to local running clubs. The Regis University Institutional Review Board approved the study protocol and all participants provided written informed consent prior to participating in the study.

Thirty runners (13 men and 17 women) voluntarily consented to participate in this study. The mean age of the participants was 31.8 years, with a range of 20 to 48 years. All participants selected for this study met the following inclusion criteria: (1) between the ages of 18 to 50 years, (2) running on average at least 20 miles per week for one-year prior to participation in the study, (3) experience running on a treadmill, (4) no history of lower extremity congenital or traumatic deformity or previous surgery that resulted in altered bony alignment, and (5) no acute injury three months prior to the start of the study that has led to the inability to run.

Upon arrival to the lab, each participant's height, weight, shoe length, blood pressure and heart rate were measured and recorded. Participants also completed a survey regarding their history of running-related injuries. Once these data were collected, participants completed a six-minute warm-up run on the treadmill to acclimate to the treadmill

(Bertec Corporation, Columbus, OH) and to determine their preferred treadmill speed described to the participants as their "normal training run pace." During the final minute of the six-minute warmup, a member of the research team measured the cadence of each participant by counting foot strikes in a 15-second time frame and multiplying by four. After the completion of the warm-up period, one researcher (MFR) placed reflective markers on selected anatomic landmarks including bilateral anterior superior iliac spines, bilateral posterior iliac spines, left lateral epicondyle of the knee, left lateral malleolus, left posterior lower leg over the Achilles tendon (two markers), and over the posterior midline of the left shoe (two markers). These locations are consistent with the marker set used in a previous study examining the reliability of 2-dimensional kinematic analysis.[22] Another researcher (CM) placed the active marker clusters (infrared-emitting diodes) for the 3D optoelectric motion capture system (3D Investigator, Northern Digital, Inc., Ontario, Canada) on the pelvis, thigh, shank and foot. Using the digital markers and rigid body references, a digitizer was used to establish digital markers directly over the reflective markers for the 2D video.

After the reflective and digital markers were placed on the participant, a one-second static trial was collected to obtain reference force plate and marker data. The participants then were asked to start running at their predetermined preferred speed on the treadmill. Digital recordings at 240 frames per sec (fps) were collected using two single high-speed cameras (SONY DSC-RX100 IV) at orthogonal angles (frontal and sagittal planes) and, concurrently, the 3D motion capture data was collected at 240 frames per second for thirty seconds. The ground reaction forces were collected at 1200 Hz through the force plates embedded in the instrumented treadmill (Bertec Corporation, Columbus, OH) and were internally synchronized with the 3D motion capture data.

The following six sagittal plane kinematic variables were assessed on the left lower extremity for all 30 runners using both the 2D and 3D data: 1) angle of the shoe to treadmill at initial contact (SHOE_ANG), 2) angle of the lower leg relative to vertical at initial contact (LEG_ANG), 3) knee flexion at initial contact (KN_FL_IC), 4) knee flexion at midstance (KN_FL_MS), 5) vertical position of the estimated center of mass (center of line connecting ASIS and PSIS) at midstance, and 6) vertical position of the estimated center of mass at double float. KN_FL_IC was subtracted from KN_FL_MS 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 total vertical excursion of the center of mass (COM_VtEx). All angles were measured in degrees and all distance measurements were recorded in centimeters. The fifth step was analyzed for both the 2D and 3D data. For the 2D data captured using the digital cameras, the data were analyzed using a free-access video analysis software program (Kinovea, version 0.8.15, http://www.kinovea.org). In a previously published study, in comparison to another rater with a similar level of experience, the investigator who measured al 2D data in this study (MFR) demonstrated high intra-rater levels of reliability ranging from 0.88 to 0.98 (ICC) for sagittal plane variables and between 0.45 and 0.96 for frontal plane variables.[22] For the 3D data, joint angles were computed from a six degree of freedom rigid body model in Visual3D (C-Motion, Inc., Germantown, MD).

Ground reaction force data were filtered using a fourth-order, zero-lag low-pass Butterworth filter with a 30 Hz cutoff. Similar to the Wille study,[20] the peak vertical component of the ground reaction force (Vert_GRF) and the average loading rate (AVG_LR) were measured for five consecutive running cycles for the left and right lower extremities with the average of the five cycles used for further analysis. The Vert_GRF was reported in body weight (BW) and AVG_LR was reported in BW/sec. As in the Wille et al study,[20] the AVG_LR was defined as the rate of change in the vertical GRF from 20% to 80% of the period beginning with initial contact to the vertical force impact peak. Peak braking force (PK_BRK) was defined as the peak posteriorly directed ground reaction force following heel strike, reported in N/kg.

In addition to descriptive statistics, t-tests were used to assess the differences between the mean 2D and 3D kinematic values. Kinematic variables collected using the 2D data were used in the prediction formula from our previous research to estimate vertical ground reaction force (VERT_GRF) and average loading rate (AVG_LR).[21] A stepwise forward linear regression was used to determine if a set of kinematic and spatiotemporal variables collected in this study were predictive of VERT_GRF, AVG_LR, and PK_BRK. Differences were assessed between estimated kinetic variables using earlier published prediction equations and the new prediction equations with the actual measured kinetic variables collected with the force plate instrumented treadmill. To compare the prediction equations to those in previous published studies,[20,21] the amount of variance in the kinetic parameters explained by the kinematic measures and step rate for each particular model was reported as the R^2 value as well as the adjusted R^2 value which adjusts for the number of terms in a model. Statistical analyses were performed using SPSS Statistics, Version 26 (IBM Corporation, Armonk, New York 10504). An alpha level of .05 was established for all tests of significance.

RESULTS

Participant characteristics (mean ± SD) for the 30 runners included age (31.8 ± 8.4 years), height (174.6 ± 10.6 cm), mass (70.9 ± 14.3 kg), preferred step rate (175 ± 6.0 steps per minute), and running speed (3.15 ± 0.39 m/s). Descriptive statistics for all 2D and 3D kinematic measurements are listed in Table 1. We found that SHOE_ANG, LEG_ANG, KN_FL_IC, and KNEE_FL_MS 2D measurements were all significantly different from the 3D measurements. However, the actual mean differences between the 2D and 3D values were 2.7° for SHOE_ANG, 1.4° for LEG_ANG, 2.1° for KN_FL_IC, and 4.9° for KNEE_FL_MS. The vertical COM excursion measures using the 2D and 3D systems were not significantly different, nor was the cadence measured by a

Table 1. Means and standard deviations for 2D and 3D kinematic and spatiotemporal variables (*units*).

VARIABLE	2D	3D	p-value
Angle of Shoe to Treadmill at Initial Contact (SHOE_ANG) (*degs*)	1.27 ± 7.78	3.96 ± 8.70	.000
Angle of Leg at Initial Contact (LEG_ANG) (*degs*)	4.33 ± 2.89	5.67 ± 2.27	.032
Knee Flexion Angle at Initial Contact (KN_FL_IC) (*degs*)	12.70 ± 4.48	10.62 ± 4.78	.006
Knee Flexion at Midstance (KN_FL_MS) (*degs*)	38.30 ± 4.10	33.35 ± 4.81	.000
Total Knee Flexion (KN_FL_Tot) (*degs*)	25.61 ± 4.84	22.74 ± 3.47	.000
Total Vertical Excursion of Center of Mass (COM_VtEx) (*cm*)	7.30 ± 1.53	7.26 ± 1.65	.873
Cadence (*steps/min*)	174.93 ± 6.03	174.70 ± 8.94	.819

Table 2. Correlation matrix of 2D and 3D kinematic and spatiotemporal variables

	3D[c] SHOE_ANG	3D LEG_ANG	3D KN_FL_IC	3D KN_FL_MS	3D KN_FL_TOT	3D COM_VtEx	3D Cadence
2D[b] SHOE_ANG[d]	.901[a]						
2D LEG_ANG[e]		.223					
2D KN_FL_IC[f]			.652[a]				
2D KN_FL_MS[g]				.658[a]			
2D KN_FL_Tot[h]					.668[a]		
2D COM_VtEx[i]						.731[a]	
2D Cadence							.799[a]

[a]Correlation is significant at .01
[b]2D = two-dimensional
[c]3D = three-dimensional
[d]SHOE_ANG = Angle of the Shoe to Treadmill at Initial Contact
[e]LEG_ANG = Angle of the Leg to Vertical at Initial Contact
[f]KN_FL_IC = Knee Flexion Angle at Initial Contact
[g]KN_FL_MS = Knee Flexion at Midstance
[h]KN_FL_Tot = Total Knee Flexion
[i]COM_VtEx = Total Vertical Excursion of the Center of Mass

research team member and the 3D system. A correlation matrix with the correlations between the 2D and 3D kinematic and spatiotemporal variables is provided in Table 2.

The prediction equations developed in the study using stepwise linear regression for VERT_GRF, AVG_LR, and PK_BRK were as follows:

$$\begin{aligned} VERT\_GRF = 1.468 &+ (speed \times .336) \\ &+ (SHOE\_ANG \times -.014) \\ &+ (LEG\_ANG \times -.006) \\ &+ (KN\_FL\_IC \times -.025) \\ &+ ((COM\ line\ to\ foot/height\ (cm)) \\ &\times -.022) + (COM\_Vt\_Ex \times .057) \end{aligned}$$

$$\begin{aligned} AVG\_LR = -13.421 &+ (SHOE\_ANG \times .757) \\ &+ (Speed \times 20.629) \end{aligned}$$

$$\begin{aligned} PK\_BRK = .759 &+ (Speed \times -.913) \\ &+ (SHOE\_ANG \times .023) \\ &+ ((COM\ line\ to\ foot/height\ (cm)) \times -.048) \\ &+ (COM\_Vt\_Ex \times -.113) \end{aligned}$$

Table 3 provides the predicted VERT_GRF, AVG_LR, and PK_BRK using the previously published[21] and new equations as well as the measured VERT_GRF, AVG_LR, and PK_BRK from the instrumented treadmill. A significant difference was found between the predicted VERT_GRF using the previous published[21] and new equations (p=.002) and between the predicted VERT_GRF using the previous published equation[21] and the measured VERT_GRF (p=.006). No difference was found between the predicted VERT_GRF using the new equation and the measured VERT_GRF. No significant differences were found between the three

Table 3. Means and standard deviations for predicted and actual kinetic variables (*units*).

VARIABLE	Estimated Values Based on Previous Equation[14]	Estimated Values Based on New Equation	Actual Values Measured by Instrumented Treadmill
Peak Vertical Component of the Ground Reaction Force (VERT_GRF) (*BW*)	2.31 ± 0.16[ab]	2.45 ± 0.26[a]	2.44 ± 0.29[b]
Average Loading Rate (AVG_LR) (*BW/sec*)	48.30 ± 11.5	52.59 ± 10.08	52.59 ± 13.6
Peak Braking Force (PK_BRK) (*N/kg*)	NA	-3.21 ± 0.44	-3.21 ± 0.60

[a] Significant difference p=.002
[b] Significant difference p=.006

AVG_LR mean values (previous prediction equation,[21] new prediction equation, and measured value). No significant difference was found between the PK_BRK using the new prediction equation and the measured value.

DISCUSSION

The objectives of this study were (1) to compare 2D video analysis of running kinematics captured with a high-speed video camera with gold standard 3D motion capture and, (2) to evaluate equations which estimated running kinetics using 2D kinematics and spatiotemporal values and modify these equations based on the current study findings. The first hypothesis was rejected as significant differences were found between the kinematic values obtained using the 2D video camera as compared to the 3D motion capture system. However, the magnitudes of these differences were 2.5° - 5°, depending on the measure. For all kinematic variables except leg angle, there were strong correlations between the 2D and 3D variables. Maykut et al[23] compared 2D and 3D video analysis of frontal plane kinematics in 24 collegiate cross-country runners. They found moderate correlations between the 2D and 3D measures of peak hip adduction and peak knee abduction although they also found significant differences between the 2D and 3D measures ranging from 1° - 4°. Weber and McClinton[24] compared 2D and 3D measurements of upper trunk rotation during running and found high correlations between the 2D and 3D values and did not find significant differences between the 2D and 3D values with differences ranging from 0° - 1.5°. Although significant differences were found between the 2D and 3D measures in this study, the magnitude of those differences and the high correlations between the measures suggest that 2D measures can be used clinically to approximate kinematic measures captured using 3D systems.

Regarding the second research objective, data were used from the 30 runners in this study to estimate VERT_GRF and AVG_LR using previously published prediction equations.[21] The comparison of the estimated kinetic values and the actual measured values showed no significant difference for AVG_LR, but there was a significant difference for VERT_GRF. In the previous work,[21] peak braking force was not estimated. Using the newly developed prediction equations calculated via a stepwise forward regression analysis for AVG_LR, VERT_GRF and PK_BRK, the inputted kinematic and spatiotemporal data resulted in estimated kinetics that were not significantly different from forces measured via a 3D system with force plates. This demonstrates an improved accuracy of estimated kinetic parameters from the previous work[21] and our second hypothesis was accepted. Two key differences between this study and the previous work include a greater sample size (n=30) and the use of the left limb only with 30 subjects rather than combining right and left limbs of 10 subjects.

In order to translate this research into the clinical setting, it is suggested that clinicians use a procedure as outlined by Souza[19] to complete a 2D digital camera video analysis of a runner. After identifying joint angles, cadence, and vertical center of mass excursion, the clinician can insert appropriate values in the equations provided in this paper to estimate loading rate, peak vertical ground reaction forces, and peak braking force. This capability increases the practicality of performing kinetic analyses in a clinical environment from cost, technical expertise, and space domains. Two-dimensional video cameras and a standard treadmill will cost far less than an instrumented treadmill and a 3D motion capture system, which together can cost $150,000-$200,000 or more. In addition, a level of expertise is required to operate and maintain these gold standard systems, which the average clinic may lack. Furthermore, 3D systems require additional infrastructure and space that would be difficult to achieve in smaller clinics.

The differences in the VERT_GRF prediction equations from the previous study[21] and the current study is the inclusion of speed as a variable and stride length as represented by a horizontal line from the COM line to the heel. There is evidence that these two variables, while not included in the previous published equation, do have an influence on vertical ground reaction force.[25-27] The AVG_LR equation in our previous paper included SHOE_ANG, LEG_ANG, KN_FL_IC, COM_VtEx, and cadence. The new equation from the current student includes only SHOE_ANG and speed, making the equation much simpler to use while increasing its predictive abilities. An equation to estimate peak braking force was added in this study based on the evidence that excessive braking force is a running-related injury risk factor.[15] The R^2 values for the new prediction equations were 0.52 for AVG_LR, 0.75 for

VERT_GRF, and 0.55 for PK_BRK. The previous published prediction equations[21] had a R^2 value of 0.51 for AVG_LR and 0.56 for VERT_GRF. Wille et al[20] reported R^2 values of 0.04 for AVG_LR, 0.48 for VERT_GRF, and 0.50 for PK_BRK. These correlation values highlight that the newly developed equations provide the best predictive abilities to date for these variables when using 2D video data, and demonstrate a substantial improvement in predicting VERT_GRF.

The results of this study support the conclusions of White et al[21] and Wille et al[20] that clinicians with access to a high-speed video camera and software for 2D data analysis can estimate average loading rate, vertical ground reaction force, and peak braking force in their patients who are runners. Estimation of these variables can be useful in the examination and treatment of running-related injuries, and can provide important pre-intervention and post-intervention data to assess the effectiveness of a selected intervention plan.

One limitation of this study was the use of a treadmill to measure kinematic and kinetic variables. There is debate in the literature about whether kinematic and kinetic variables in overground running can be replicated on a treadmill. In a recent systematic review, van Hooren et al[28] concluded, "Spatiotemporal, kinematic, kinetic, muscle activity, and muscle–tendon outcome measures are largely comparable between motorized treadmill and overground running." (p. 785) While participants were encouraged to run as they normally would, participants may also have altered their running mechanics due to the unfamiliarity of the markers that were placed on their lower extremities. A second limitation was the brevity of the sampling window. This was done recognizing time and efficiency issues in the clinic, a realistic concern of clinicians given the additional time required for data analyis using a longer sampling window. A third and final limitation is that only the left lower extremity was used. This decision was made to not combine right and left lower extremities which complicates analyses given that the two limbs of one person are not independent of each other. Future research may include both sides assessed separately.

CONCLUSION

Accurate estimations of kinetic variables can be made using spatiotemporal and kinematic variables collected using a 2D high-speed video camera. This allows clinicians without access to 3D motion capture technology and instrumented treadmills or in-ground force plates to perform running video analyses that will inform the appropriate prevention and treatment of runners.

FUNDING

This research was supported by a $1796 grant from the Regis University Research & Scholarship Committee.

CONFLICTS OF INTEREST

The authors affirm that we have no financial affiliation (including research funding) or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript, and we also affirm that we have no conflicts of interest pertaining to this study.

This study was approved by the Regis University Institutional Review Board on October 29, 2019 as an expedited review.

Submitted: November 17, 2021 CDT, Accepted: February 08, 2022 CDT

REFERENCES

1. Lange D. Number of participants in running/jogging and trail running in the U.S. from 2006 to 2017.

2. van der Worp MP, ten Haaf DS, van Cingel R, de Wijer A, Nijhuis-van der Sanden MW, Staal JB. Injuries in runners; a systematic review on risk factors and sex differences. *PLoS One*. 2015;10(2):e0114937. doi:10.1371/journal.pone.0114937

3. Lopes AD, Hespanhol Junior LC, Yeung SS, Costa LO. What are the main running-related musculoskeletal injuries? A Systematic Review. *Sports Med*. 2012;42(10):891-905. doi:10.1007/BF03262301

4. Rauh MJ, Koepsell TD, Rivara FP, Margherita AJ, Rice SG. Epidemiology of musculoskeletal injuries among high school cross-country runners. *Am J Epidemiol*. 2006;163(2):151-159. doi:10.1093/aje/kwj022

5. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*. 2002;36(2):95-101. doi:10.1136/bjsm.36.2.95

6. Tenforde AS, Sayres LC, McCurdy ML, Collado H, Sainani KL, Fredericson M. Overuse injuries in high school runners: lifetime prevalence and prevention strategies. *PM R*. 2011;3(2):125-131. doi:10.1016/j.pmrj.2010.09.009

7. Dempster J, Dutheil F, Ugbolue UC. The prevalence of lower extremity injuries in running and associated risk factors: a systematic review. *Physical Activity and Health*. 2021;5(1):133-145.

8. Ceyssens L, Vanelderen R, Barton C, Malliaras P, Dingenen B. Biomechanical Risk Factors Associated with Running-Related Injuries: A Systematic Review. *Sports Med*. 2019;49(7):1095-1115. doi:10.1007/s40279-019-01110-z

9. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *Br J Sports Med*. 2016;50(14):887-892. doi:10.1136/bjsports-2015-094579

10. Grimston SK, Nigg BM, Fisher V, Ajemian SV. External loads throughout a 45 minute run in stress fracture and non-stress fracture runners. *J Biomech*. 1994;27(6):668.

11. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38(2):323-328. doi:10.1249/01.mss.0000183477.75808.92

12. Pohl MB, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clin J Sport Med*. 2009;19(5):372-376. doi:10.1097/JSM.0b013e3181b8c270

13. Thijs Y, De Clercq D, Roosen P, Witvrouw E. Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *Br J Sports Med*. 2008;42(6):466-471. doi:10.1136/bjsm.2008.046649

14. Zifchock RA, Davis I, Hamill J. Kinetic asymmetry in female runners with and without retrospective tibial stress fractures. *J Biomech*. 2006;39(15):2792-2797. doi:10.1016/j.jbiomech.2005.10.003

15. Napier C, MacLean CL, Maurer J, Taunton JE, Hunt MA. Kinetic risk factors of running-related injuries in female recreational runners. *Scand J Med Sci Sports*. 2018;28(10):2164-2172. doi:10.1111/sms.13228

16. Duffey MJ, Martin DF, Cannon DW, Craven T, Messier SP. Etiologic factors associated with anterior knee pain in distance runners. *Med Sci Sports Exerc*. 2000;32(11):1825-1832. doi:10.1097/00005768-200011000-00003

17. Lorimer AV, Hume PA. Achilles tendon injury risk factors associated with running. *Sports Med*. 2014;44(10):1459-1472. doi:10.1007/s40279-014-0209-3

18. Lorimer AV, Hume PA. Stiffness as a Risk Factor for Achilles Tendon Injury in Running Athletes. *Sports Med*. 2016;46(12):1921-1938. doi:10.1007/s40279-016-0526-9

19. Souza RB. An evidence-based videotaped running biomechanics analysis. *Phys Med Rehabil Clin N Am*. 2016;27(1):217-236. doi:10.1016/j.pmr.2015.08.006

20. Wille CM, Lenhart RL, Wang S, Thelen DG, Heiderscheit BC. Ability of sagittal kinematic variables to estimate ground reaction forces and joint kinetics in running. *J Orthop Sports Phys Ther*. 2014;44(10):825-830. doi:10.2519/jospt.2014.5367

21. White JD, Carson N, Baum BS, Reinking MF, McPoil TG. Use of 2-Dimensional Sagittal Kinematic Variables to Estimate Ground Reaction Force during Running. *Int J Sports Phys Ther*. 2019;14(2):174-179.

22. Reinking MF, Dugan L, Ripple N, et al. Reliability of 2-dimensional video-based running gait analysis. *Int J Sports Phys Ther*. 2018;13(3):453-461.

23. Maykut JN, Taylor-Haas JA, Paterno MV, DiCesare CA, Ford KR. Concurrent validity and reliability of 2d kinematic analysis of frontal plane motion during running. *Int J Sports Phys Ther*. 2015;10(2):136-146.

24. Weber CF, McClinton S. Validity and Reliability of Video-Based Analysis of Upper Trunk Rotation during Running. *Int J Sports Phys Ther*. 2020;15(6):910-919. doi:10.26603/ijspt20200910

25. Edwards WB, Taylor D, Rudolphi TJ, Gillette JC, Derrick TR. Effects of stride length and running mileage on a probabilistic stress fracture model. *Med Sci Sports Exerc*. 2009;41(12):2177-2184. doi:10.1249/MSS.0b013e3181a984c4

26. Lobb NJ, Fain AC, Seymore KD, Brown TN. Sex and stride length impact leg stiffness and ground reaction forces when running with body borne load. *J Biomech*. 2019;86:96-101. doi:10.1016/j.jbiomech.2019.01.048

27. Nilsson J, Thorstensson A. Ground reaction forces at different speeds of human walking and running. *Acta Physiol Scand*. 1989;136(2):217-227. doi:10.1111/j.1748-1716.1989.tb08655.x

28. Van Hooren B, Fuller JT, Buckley JD, et al. Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies. *Sports Med*. 2020;50(4):785-813. doi:10.1007/s40279-019-01237-z