Ability of Sagittal Kinematic Variables to Estimate Ground Reaction Forces and Joint Kinetics in Running

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Abstract

Study Design—Controlled laboratory study, cross sectional design.

Objective—To determine if sagittal kinematic variables can be used to estimate select running kinetics.

Background—Excessive loading during running has been implicated in a variety of injuries, yet this information is typically not assessed during a standard clinical examination. Developing a clinically feasible strategy to estimate ground reaction forces and joint kinetics may improve the ability to identify those at an increased risk of injury.

Methods—Three-dimensional kinematics and ground reaction forces of 45 participants were recorded during treadmill running at self-selected speed. Kinematic variables used to estimate specific kinetic metrics included: vertical excursion of the center of mass, foot inclination angle at initial contact, horizontal distance between the center of mass and heel at initial contact, knee flexion angle at initial contact, and peak knee flexion angle during stance. Linear mixed effects models were fitted to explore the association between the kinetic and kinematic measures, including step rate and gender, with final models created using backward variable selection.

Results—Models were developed to estimate peak knee extensor moment (R^2=0.43), energy absorbed at the knee during loading response (R^2=0.58), peak patellofemoral joint reaction force

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(R^2=0.55), peak vertical ground reaction force (R^2=0.48), braking impulse (R^2=0.50), and average vertical loading rate (R^2=0.04).

Conclusions—Our findings suggest that insights into important running kinetics can be obtained from a subset of sagittal plane kinematics common to a clinical running analysis. Of note, the limb posture at initial contact influenced subsequent loading patterns in stance.

Keywords

gait analysis; ground reaction forces; knee; patellofemoral; running injury

A number of risk factors have been identified to predict the occurrence of running-related injuries, including excessive ground reaction forces (GRF) and joint loads.[11] Despite this, GRFs and joint loads during running are typically not measured in clinical practice due, in part, to cost, equipment availability, and complexity of analysis. As a result, clinical gait analysis of an injured runner is commonly limited to a qualitative kinematic assessment using a single video camera. Further, gait retraining techniques (eg, step rate modification) involve kinematic adjustments with the goal of altering the associated kinetics, and ultimately injury risk.[6, 8] Thus, identifying simple, easily obtained kinematic measures that provide an estimate of important kinetic metrics may have substantial clinical value in the management of running injuries.

The purpose of this study was to determine whether kinetic metrics commonly used to reflect lower extremity loading during running could be estimated from discrete sagittal plane kinematic variables. Further, we assessed the strength of the associations under repeated conditions involving running at various step rates and between genders.

METHODS

Participants

Forty-five adult volunteers familiar with treadmill running participated in this study. All participants ran a minimum of 24.1 km/wk for at least 3 months prior to enrollment. Participants were excluded if they had a lower extremity injury in the prior 3 months; had prior lower extremity surgery; or currently had pain in their back or lower extremities while running. The testing protocol was approved by the Health Sciences Institutional Review Board at the University of Wisconsin-Madison, and participants provided written informed consent in accordance with institutional policies.

Data Acquisition

Participants ran on a treadmill at a self-selected, moderate intensity speed, at their preferred step rate, as well as step rates 10% above and below preferred. The self-selected speed was maintained across all step rate conditions. A digital audio metronome was used to facilitate the appropriate step rate. Whole body kinematics were recorded (200 Hz) using an 8-camera passive marker system (Motion Analysis Corporation, Santa Rosa, CA), which tracked 40 reflective markers with 21 of them located on anatomical landmarks. Three dimensional GRFs were simultaneously recorded (2000 Hz) using an instrumented treadmill (Bertec Corporation, Columbus, OH).

Data processing methods followed procedures previously described.[6] In brief, an upright calibration trial was performed to establish joint centers, body segment coordinate systems, segment lengths, and local positions of tracking markers. The body was modeled as a 14-segment, 31 degree of freedom articulated linkage. Anthropometric properties of body segments were scaled to each individual using the participant's height, mass, and segment lengths.[4] To compute whole body center of mass (COM), each model segment position was multiplied by the respective mass, then summed and divided by the total mass of the body.[6] A segment-by-segment inverse dynamics analysis was used to calculate joint moments from the GRFs and kinematic data. Joint powers were computed as the product of the moment and angular velocity for each joint. Patellofemoral joint force was estimated for 26 participants using previously described procedures[8] involving a lower extremity musculoskeletal model[1] with a patellar tendon that remained a constant length. Numerical optimization was used to compute the patellar tendon and lower extremity muscle forces necessary to generate the measured joint angle accelerations at each frame of motion. The magnitude of the patellofemoral joint reaction force was then computed through force balance. Five successive strides of the right limb for each participant were analyzed for each step rate condition.

Outcome Measures

Kinematic variables included: COM vertical excursion over a gait cycle, foot inclination angle at initial contact (IC) with respect to the ground and normalized to standing posture, horizontal distance between the COM and heel at IC, knee flexion at IC, and peak knee flexion during stance (**FIGURE 1**). These variables were chosen as they are all easily identifiable sagittal plane measures that are frequently modified during gait retraining.[2, 6, 8]

Calculated kinetic metrics were: peak knee extensor moment, mechanical energy absorbed about the knee during loading response with loading response defined from IC to peak knee flexion angle during stance, peak patellofemoral joint reaction force, peak vertical GRF, braking impulse, and average loading rate defined as the rate of change of the vertical GRF from 20 to 80% of the period from IC to vertical impact peak (**FIGURE 2**). In the absence of a distinct impact peak, an estimate of its occurrence was determined as a function of the overall peak vertical GRF.[13] Mechanical energy absorbed and braking impulse were calculated by numerically integrating the negative portions of the knee joint power curve and anterior-posterior GRF, respectively. All kinetic metrics were normalized to participants' body mass.

Statistical Analysis

Data points deviating more than 3 standard deviations from average were defined as outliers and removed from the analysis. Linear mixed effects models were developed to explore the association between outcomes (kinetic metrics) and covariates (kinematic variables and step rate condition). Gender was also introduced as a covariate due to its influence on running mechanics.[3, 5] Final models were developed using backward variable selection with significance for inclusion set *a priori* at $P<0.05$. The amount of variance in the kinetic parameters explained by the kinematic measures within each respective model was reported as the adjusted R^2 value. Random participant-specific intercepts were included to account

for the correlation among repeated measures on the same participant. Data from all 3 step rate conditions were included in the analysis, as it allowed for a greater number of within participant relationships to be analyzed. The validity of the models was maintained by including step rate as a covariate. We initially tested the overall effect of step rate, and if not significant, step rate was removed from the model. If step rate was significant then the pairwise comparisons were conducted. In addition, if an interaction term between 2 covariates was determined to predict the kinetic metric, both covariates were required to be included into the model. All analyses were performed utilizing R version 2.15.1 (The R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

All data from 1 participant were removed as the participant's preferred running speed (1.4 m/s) prevented a consistent flight phase. As such, data from 44 participants (25 males) were used to develop the linear regression models. Participant characteristics (mean ± standard deviation) included: age, 32.7 ±15.5 yrs; height, 176.3 ±10.3 cm; mass, 69.5 ±13.1 kg; preferred step rate, 173 ±8.9 steps/min; running speed, 2.94 ±0.42 m/s; and average weekly running volume, 29.8 ±15.5 km/wk. The values for mechanical energy absorbed about the knee for 3 participants were identified as outliers and removed.

The final models for each kinetic parameter, with the exception of loading rate, were comprised of 1 to 3 kinematic measures (plus step rate) and had adjusted R^2 values ranging from 0.43 to 0.58 (**TABLE**, **FIGURE 2**). For loading rate, only step rate was included in the final model (adjusted $R^2 = 0.04$). Foot inclination angle at IC was a common predictive factor, appearing in 4 of the 6 models, while knee flexion angle at IC and gender were not included in any of the final models. Scatterplots of the observed and estimated kinetic parameters are shown in **FIGURE 3**.

DISCUSSION

The purpose of this study was to determine if selected kinetic metrics during running could be estimated from discrete sagittal plane kinematic variables. The results are encouraging as significant associations were identified between easily measurable kinematic variables and kinetic metrics often associated with common running injuries. Thus, this information could be used to infer potential targets of treatment in a clinical kinematic analysis of injured runners.

Independent kinematic variables appearing more frequently in the models included COM vertical excursion, foot inclination angle at IC, and heel to COM horizontal distance at IC. The presence of the latter 2 measures suggests that the limb posture at IC has an influence on subsequent loading patterns in stance. This information may be important in clinical running analysis and ensuing retraining strategies to modify running mechanics. That is, to reduce the GRFs and knee joint loads during running, gait retraining is likely to include strategies aimed at altering limb posture at landing and/or reducing the COM vertical excursion over the gait cycle. Examples of such strategies include increasing step rate and avoidance of a heel-strike at IC.[2, 6, 8] Knee flexion angle at IC was not included in any of the

final models, indicating its limited value in relation to the other kinematic measures that better reflect whole body motion. Further, gender was not included in any of the final models, revealing the relationship between the kinematic variables and kinetic metrics to be consistent for men and women.

The magnitude of association between running kinematic and kinetic parameters observed in this study was consistent with others. A multivariate regression analysis has been used to determine kinematic correlates of the free moment and combined loads during running with R^2 values ranging from 0.16 to 0.78.[10] Given the values observed from both studies, it is plausible that only a moderate association can be achieved using a minimal set of kinematic measures. Indeed, considering the substantial number of kinematic variables that could influence running kinetics, being able to explain up to 58% of the variance with 3 or fewer kinematic variables (plus step rate) is somewhat impressive. Nonetheless, additional factors should be sought to refine our models.

The model developed to estimate loading rate was comprised only of step rate and had the lowest R^2 value (0.04) indicating its limited usefulness. Because the loading rate occurs so early in stance, swing phase kinematics may provide a better estimate than those we selected at IC or later. Thigh position at mid-swing has been found to be the best estimate for loading rate, although still having a low adjusted R^2 value (0.15).[12]

A step rate interaction term in the models indicates that the contribution of the specific kinematic measure to the kinetic parameter varies with the step rate condition. For example, the contribution of COM vertical excursion to estimating peak vertical GRF is greater when running at a step rate 10% above preferred rate; whereas its contribution is less when running at a step rate 10% below preferred rate, as indicated by the negative interaction parameter (**TABLE**). Similarly, the model used to estimate braking impulse indicates the effect of heel to COM horizontal distance at IC varies with step rate. In the remaining models, the relationship between the kinematic measures used to estimate the respective kinetic parameter holds true across all step rate conditions.

Sagittal plane kinematic measures were chosen due to the practicality of identifying them in a clinical setting. Because running is largely a sagittal plane movement, kinematic values can be obtained with greater reliability than frontal or transverse plane motions.[7, 9] Although a computerized 3D motion capture system was used in the present study, a 2D analysis is likely sufficient to capture the specified kinematic measures given the strong correlations between 2D and 3D sagittal plane motions during running.[9] Future work will confirm that the relationships identified in the current study can be generalized to procedures involving a simplified 2D approach employing a single video camera with adequate frame rate (greater than 100 frames per second) to capture specific gait events, such as IC and midstance. Further, cross-validation of the models with an additional sample of runners is needed before one can have confidence in their predictive ability.

CONCLUSION

Our findings indicate that sagittal plane kinematic variables can estimate several important GRF and knee joint kinetic metrics. These defined relationships provide clinicians with a simple approach to estimate running kinetics that may prove useful in treating runners with a lower extremity injury or identifying runners at increased risk of injury.

ACKNOWLEDGEMENTS

REFERENCES

1. Arnold EM, Ward SR, Lieber RL, Delp SL. A model of the lower limb for analysis of human movement. Ann Biomed Eng. 2010; 38:269–279. [PubMed: 19957039]

2. Cheung RT, Davis IS. Landing pattern modification to improve patellofemoral pain in runners: a case series. J Orthop Sports Phys Ther. 2011; 41:914–919. [PubMed: 22031595]

3. Chumanov ES, Wall-Scheffler C, Heiderscheit BC. Gender differences in walking and running on level and inclined surfaces. Clin Biomech (Bristol, Avon). 2008; 23:1260–1268.

4. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech. 1996; 29:1223–1230. [PubMed: 8872282]

5. Ferber R, Davis IM, Williams DS 3rd. Gender differences in lower extremity mechanics during running. Clin Biomech (Bristol, Avon). 2003; 18:350–357.

6. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc. 2011; 43:296–302. [PubMed: 20581720]

7. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res. 1989; 7:849–860. [PubMed: 2795325]

8. Lenhart RL, Thelen DG, Wille CM, Chumanov ES, Heiderscheit BC. Increasing running step rate reduces patellofemoral joint forces. Med Sci Sports Exerc. 2014; 46(3):557–564. [PubMed: 23917470]

9. McClay I, Manal K. Three-dimensional kinetic analysis of running: significance of secondary planes of motion. Med Sci Sports Exerc. 1999; 31:1629–1637. [PubMed: 10589868]

10. Meardon, SA.; Edwards, WB.; Derrick, TR. Kinematic correlates of the free moment and combined loads during running. American Society of Biomechanics Annual Conference; Palo Alto, CA: 2007.

11. Messier SP, Legault C, Schoenlank CR, Newman JJ, Martin DF, DeVita P. Risk factors and mechanisms of knee injury in runners. Med Sci Sports Exerc. 2008; 40:1873–1879. [PubMed: 18845979]

12. Schmitz A, Pohl MB, Woods K, Noehren B. Variables during swing associated with decreased impact peak and loading rate in running. J Biomech. 2014; 47:32–38. [PubMed: 24200340]

13. Wille, CM.; Heiderscheit, BC. Methods of calculating loading rate during running in the absence of an impact peak.. 7th World Congress of Biomechanics; Boston, MA. July 2014;
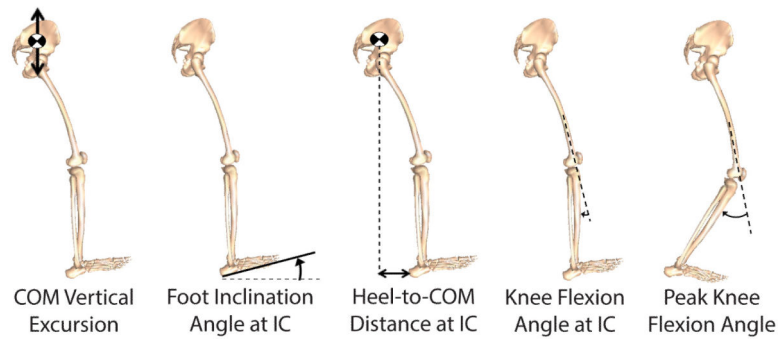
COM Vertical Excursion | Foot Inclination Angle at IC | Heel-to-COM Distance at IC | Knee Flexion Angle at IC | Peak Knee Flexion Angle

FIGURE 1.

Sagittal plane kinematic measures used to estimate ground reaction forces and joint kinetics during running. Running step rate condition and gender were also considered in the models. Abbreviations: COM, center of mass; IC, initial contact.
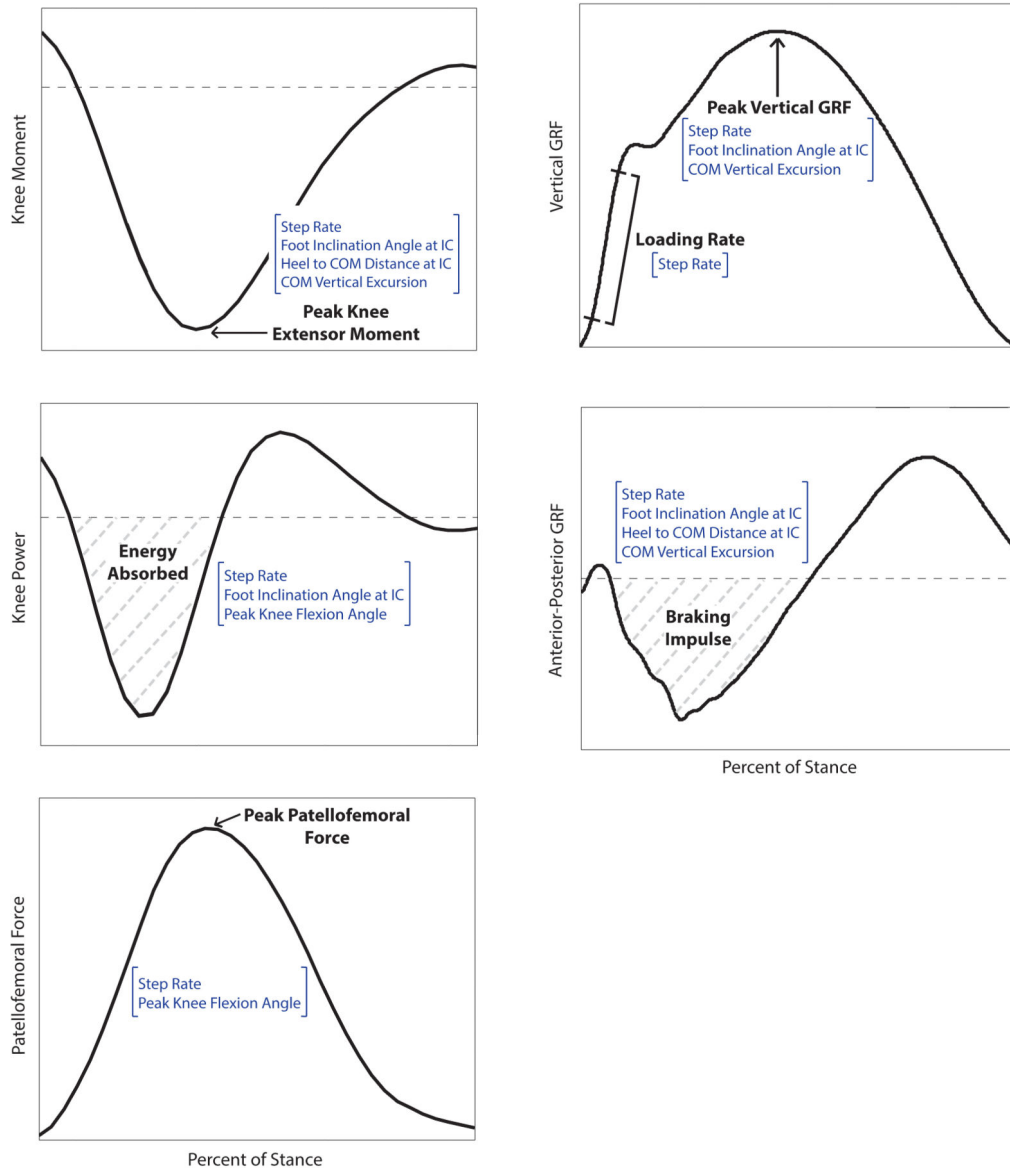
FIGURE 2.
Ground reaction forces (GRFs) and knee joint kinetics during the stance phase of running were each estimated from a subset of kinematic measures including step rate. Abbreviations: COM, center of mass; IC, initial contact
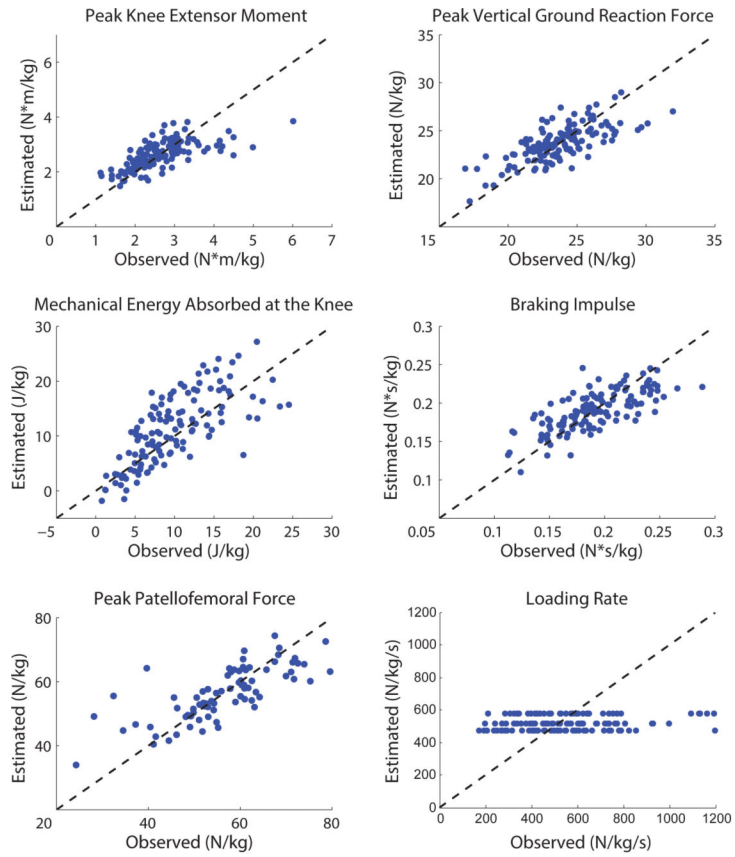
FIGURE 3.
Observed values (experimentally measured) and estimated values (model derived) for each kinetic metric.

TABLE

Linear mixed effects models defining the extent to which kinematic measures including step rate condition can be used to estimate kinetics, with final models created using backward variable selection.

	Adjusted R^2	Parameters	*P*-value
Peak Knee Extensor Moment	0.43		
Intercept		0.39	0.440
−10% Condition		−0.29	0.037
+10% Condition		0.16	0.176
Foot Inclination Angle at IC		0.02	0.003
Heel to COM Distance at IC		6.82	0.001
COM Vertical Excursion		16.88	0.002
Knee Sagittal Plane Energy Absorption	0.58		
Intercept		−0.03	0.902
−10% Condition		−0.14	<.0001
+10% Condition		0.04	0.212
Foot Inclination Angle at IC		−0.03	<.0001
Peak Knee Flexion Angle		−0.01	0.044
Peak Patellofemoral Force	0.55		
Intercept		−4.38	0.328
−10% Condition		3.76	<0.001
+10% Condition		3.10	<0.001
Peak Knee Flexion Angle		1.32	<0.001
Peak Vertical Ground Reaction Force	0.48		
Intercept		12.62	<0.001
−10% Condition		−0.19	0.824
+10% Condition		−0.54	0.515
Foot Inclination Angle at IC		−0.05	<0.001
COM Vertical Excursion		132.00	<0.001
−10% Condition: COM Vertical Excursion		−16.30	0.076
+10% Condition: COM Vertical Excursion		18.91	0.079
Braking Impulse	0.50		
Intercept		0.07	0.003
−10% Condition		0.03	0.082
+10% Condition		−0.02	0.174
Foot Inclination Angle at IC		−0.001	0.021
Heel to COM Distance at IC		0.47	<0.001
COM Vertical Excursion		0.87	0.001
−10% Condition: Heel to COM Distance at IC		−0.31	0.102

	Adjusted R^2	Parameters	*P*-value
+10% Condition: Heel to COM Distance at IC		0.34	0.136
Loading Rate	0.04		
Intercept		553.04	<0.001
−10% Condition		56.28	0.018
−10% Condition		−42.44	0.074

Abbreviations: COM, center of mass; IC, initial contact