GROUND REACTION FORCES DURING COMPETITIVE TRACK EVENTS: A MOTION BASED ASSESSMENT METHOD

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A motion based approach to generating vertical ground reaction forces (VGRF) from the motion of sprint running could be a useful analytical tool. The spring-mass model has been used for this purpose; however, the invariant pattern predicted by the model is not fully consistent with the force-time waveforms of competitive sprint athletes. The recently introduced two-mass model provides an alternative method that might generate better representations of sprinter's force-time waveforms. Here we used both models to generate kinematic-averaged force-time waveforms from 4 sprint athletes in an IAAF 100-meter race from 360 Hz video data. We found substantial differences in the waveform patterns predicted by the two models. The two-mass model predicted waveform had greater peak forces (4.75 W_b) that occurred earlier in contact (28 ms) vs that of the spring mass model.

KEY WORDS: two-mass model, performance, sprinting, spring-mass model, locomotion.

INTRODUCTION: High-speed running requires striking the ground forcefully enough to abruptly alter the vertical accelerations of the body's mass during each step. Faster runners are able to do so at greater speeds because they hit the ground more forcefully in relation to body mass and therefore with the more brief foot-ground contact times required (Weyand et al. 2000). The vertical ground reaction forces (VGRF) observed at swift sprinting speeds can reach peak values up to five times body weight and are a critical contributor to performance capabilities. Recently, elite sprinters have been shown to have a characteristic pattern of ground force application that maximizes surface reaction forces and running velocities (Clark & Weyand, 2014). Accordingly, the ability to assess vertical ground reaction forces outside the laboratory in competition settings would be potentially valuable (Weyand et al. 2010).

For the past quarter century, the spring-mass model (Blickhan, 1989) has been the most popular approach to characterizing running mechanics. The simplicity of the model allows for the generation of VGRF waveforms from nothing more than contact and aerial times (Taylor & Beneke 2012, Morin et al. 2015, McGowan et al. 2012). This widely used model treats the leg as a massless spring attached to a point mass which results in a vertical force-time waveform which takes the shape of a half-sine wave with a waveform peak force that occurs halfway through the contact period regardless of the circumstances. The model has been used previously in both the lab (McGowan et al. 2012) and track settings (Taylor & Beneke 2012, Morin et al. 2015) to model running mechanics at high speeds. However, the model is incapable of predicting the pattern variations responsible for performance differences among runners.

The recently developed two-mass model of running mechanics, like the spring-mass model, is capable of generating vertical ground reaction force-time waveforms from limited kinematic information. This newer model does appear to be capable of accurately predicting the instantaneous forces present across the full force-time waveform regardless of speed and foot-strike mechanics (Clark et al. 2017). The model requires only body mass and three stride-specific measures as inputs: contact time, aerial time and ankle acceleration. Thus, unlike the simple spring-mass model, the two-mass model has the potential to assess the mechanical features of sprinters' gaits that influence performance. Moreover, the stride-specific inputs the model requires can be acquired from either video or motion data from the ankle.

Here, we conducted a preliminary investigation comparing the waveforms generated by the two-mass vs. the spring-mass model. We did so using the same sprint running video footage taken from an IAAF 100-meter race. We hypothesized that waveform peak force values, time to peak and overall waveforms shapes would differ substantially across the two methods.

METHODS: Motion data were acquired from video footage from a 2011 IAAF Track and Field Diamond League 100m race in Monte Carlo, Monaco during which a high-speed camera acquired sagittal plane footage while moving in parallel with the athletes throughout the event. The footage was recorded at a frame rate of 360 Hz and provided unobstructed contact and aerial periods of six steps for four runners. Confidence in the estimated kinematic variables from the video was supported by similarities between our values for one athlete and those previously reported for the same athlete in other 100M races (Krzysztof et al. 2013). The athletes' running velocities were determined from the frame rate and known distance between marks on the track. The mean performance time of the four athletes analyzed in the race was 9.94 seconds.

Spring-mass model waveforms were generated using contact and aerial time in accordance with the procedure of Clark & Weyand (2014). Two-mass model waveforms were generated from contact time, aerial time and estimated ankle velocity on impact. Contact times (t_c) were determined by assessing the average number of frames the foot was on the ground during six consecutive steps and multiplying by the frame time. Aerial times (t_a) were determined from the time between steps when neither foot was in contact with the ground.

The third input required by the two-mass model, the vertical acceleration of the lower-limb during impact is determined by the vertical velocity (Δv_1) of the limb at impact and the time (Δt_1) to "bottom out", or reach a vertical velocity of zero in the post-impact period. These values were estimated from running velocity based on empirical relationships established using a database of elite sprinters for whom precision data were available from prior laboratory testing. The velocity of the lower limb at impact was quantified as Δv_1 = 0.25 x running velocity. Lower-limb deceleration time was approximated by Δt_1 = 0.25 x contact time (Clark et al, 2017; see Figures 3, 5, 6 and Table 2).

A single, kinematic-averaged waveform was generated from 24 steps for both the spring-mass and the two-mass models (n=6 steps x 4 sprint athletes). The respective waveforms were compared for the following variables: peak force, stance-average force and loading rate expressed in body weights per second (Peak force/time to peak force).

RESULTS: For the steps analyzed from the four athletes, the mean running velocity was 11.7 ms^{-1}. Based on the running speeds and contact times calculated for each subject, the mean vertical velocity of the lower-limb on impact (Δv_1) was 2.94 ms^{-1} and the deceleration time to a lower-limb vertical velocity of zero (Δt_1) was 22.6 ms.

Table 1
Model Predicted Vertical Ground Reaction Force Data

	Two-Mass Model	Spring-Mass Model	% diff
Fz Average (W_b)	2.47	2.47	0
Fz Peak (W_b)	4.75	3.88	18.32
Time to Peak (ms)	28	45	-60.71
Loading Rate (W_b/ms)	0.170	0.086	49.17

Values are means for 24 footfalls from four sprinters

The two-mass and spring-mass models generated equal impulses due to the common contact and aerial time values utilized across models (Table 1). However, peak force and time to peak force values differed substantially. The spring-mass model predicted a vertical force peak that was 18 % less than that generated by the two-mass model (Table 1). The time to peak force occurred 17 milliseconds later in the spring-mass vs. the two-mass model's kinematic-averaged waveform.

As a direct consequence of the peak force and timing differences, model predicted loading rates were two times greater for the two-mass vs. spring-mass model (Table 1).

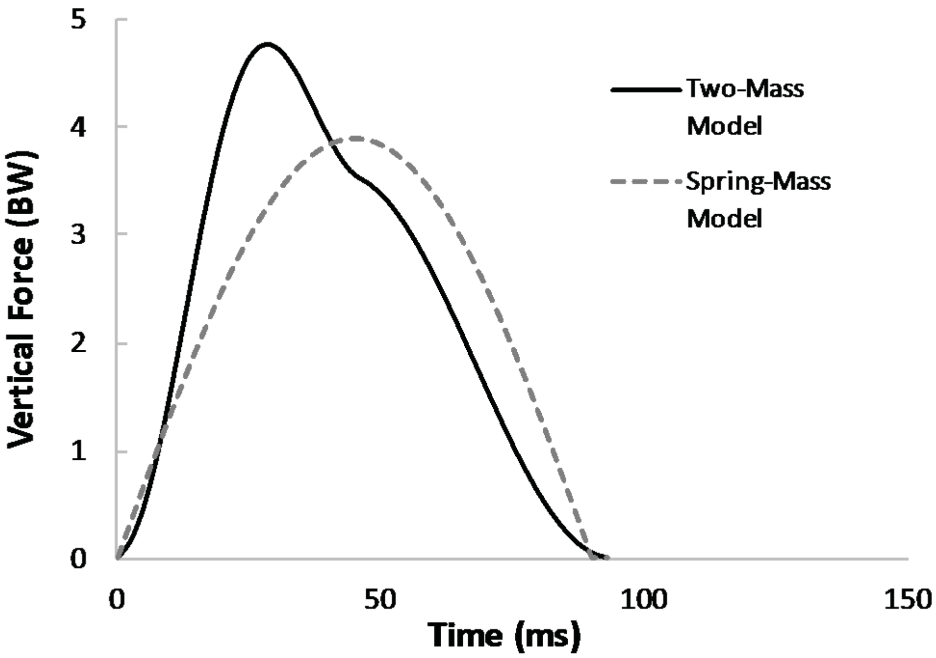

Figure 1: Kinematic-averaged sprint running ground reaction force-time waveforms generated by the two-mass and spring-mass models from 24 footfalls (n = 6 per athlete) at a mean running velocity of 11.7 meters per second.

CONCLUSION: As hypothesized, the shape characteristics, respective peak forces, and times to peak force of the kinematic-averaged waveforms generated with the two-mass vs. spring-mass models varied considerably. Directly measured ground reaction force measurements were not available from the steps analyzed. Therefore, comparisons of the relative validity of the differing model-generated waveforms were not possible. However, the ensemble-averaged waveform generated by the two-mass model did conform more closely to the measured ground reaction force-time waveforms currently in the literature for competitive sprint athletes (Bezodis, 2008; Clark & Weyand, 2014; Kuitunen et al, 2002) than did that of the spring-mass model.

One potential drawback of the two-mass vs. spring-mass model is the additional requirement of lower-limb motion data for the former. In the present application, the high-speed video footage did not allow Δv_1 *and* Δt_1 to be reasonably acquired or estimated. In practice, measured lower-limb impact velocities (Δv_1) and post-impact stopping times (Δt_1) may be acquirable with the implementation of a marker or other visual preparation of a specific landmark. Therefore, in this case, experimental use of the two-mass model required estimating both lower limb velocity (Δv_1) and stop time (Δt_1). Although these estimates might deviate somewhat from the mean values that were actually present under the race conditions, any error introduced is likely to be small due to two factors. First, there was minimal variation present from the best-fits obtained to our precision kinematic measurements in the laboratory on our population of national and international caliber sprinters. Second, in general the mechanics sprinters utilize to maximize ground forces to attain elite speeds appear to vary minimally across different athletes of similar competitive caliber (Clark & Weyand, 2014; Clark et al., 2017)

We conclude that the two-mass model is a promising and potentially practical way to estimate sprinting ground reaction forces in situations where direct force measurements are not possible.

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