Using the spring-mass model for running: Force-length curves and foot-strike patterns

Abstract

Background: The spring-mass model is commonly used to investigate the mechanical characteristics of human running. Underlying this model is the assumption of a linear force-length relationship, during the stance phase of running, and the idea that stiffness can be characterised using a single spring constant. However, it remains unclear whether the assumption of linearity is valid across different running styles.

Research question: How does the linearity of the force-length curve vary across a sample of runners and is there an association between force-length linearity and foot-strike index/speed?

Methods: Kinematic and kinetic data were collected from twenty-eight participants who ran overground at four speeds. The square of the Pearson's correlation coefficient, R^2, was used to quantify linearity; with a threshold of $R^2 \geq 0.95$ selected to define linear behaviour. A linear mixed model was used to investigate the association between linearity and foot-strike index and speed.

Results: Only 36-46 % of participants demonstrated linear force-length behaviour across the four speeds during the loading phase. Importantly, the linear model showed a significant effect of both foot-strike index and speed on linearity during the loading phase ($p = 0.003$ and $p < 0.001$, respectively).

Significance: This study showed that the assumption of a linear force-length relationship is not appropriate for all runners. These findings suggest that the use of the spring-mass model, and a constant value of stiffness, may not be appropriate for characterising and comparing different running styles. Given these findings, it may be better to restrict the use of the spring-mass model to individuals who exhibit linear force-length dependence. It would also be appropriate for future studies, characterising stiffness using the spring-mass model, to report data on force-length linearity across the cohort under study.

Keywords: Running, Spring-mass model, Force-length relationships, Stiffness, Modelling

Introduction

The spring-mass model is a simple biomechanical model that can be applied to bouncing gaits, e.g. running [1-3]. Although the spring-mass model is simple, it has had success in modelling certain characteristics of running, such as vertical impulse. However, it consistently overestimates others, such as the vertical centre of mass (CoM) displacement [1]. This approach assumes the human body can be modelled using a single mass bouncing on a massless linear spring, where the movement of the mass reflects that of the body's CoM and is determined by the characteristics of the spring and the mass, the most fundamental of which is stiffness [3]. The spring-mass model has led authors to quantify, and use, stiffness as a descriptive parameter of running [4-7].

For the spring-mass model, the stiffness represents that of the whole body, yet it is often referred to as 'leg stiffness' or 'lower limb stiffness' as the change in length of the spring is often estimated from the change in length of the leg [1]. According to Hooke's law, and assuming a linear relationship, this single value of 'stiffness' can be determined from the slope of the force-length curve. In the stance phase of running, this slope quantifies the relationship between the ground reaction force (GRF) vector and the CoM movement. The appearance of linearity in the force-length curve suggests the body may behave similarly to a passive system in certain cases, and has led authors to calculate stiffness from the maximum force and maximum displacement [1, 4, 6, 8]; often without assessing the force-length curve. If the force-length curve appears linear, then stiffness can be a useful way of characterising runners and has been used to investigate the effects of altering step frequency and contact time [7], speed [4] and changing footwear [9]. However, if the force-length curve is not linear, then the use of a single constant value of stiffness may not be appropriate.

The spring-mass model and stiffness can be useful for investigating between-group differences and the effect of interventions, such as training or footwear, within certain populations [6, 10-12]. This model is often used for rearfoot strikers [10], groups of runners where the foot-strike pattern is not identified [6, 11, 12], or where forefoot and rearfoot strikers are grouped [6, 11]. However, the existence of an impact peak in the vertical ground reaction force (GRF), a common characteristic of rearfoot running [13, 14], may lead to a significant non-linearity in the force-length curve. Other characteristics of running may also lead to differences in force-length behaviour, such as lower limb kinematic patterns, joint moments and muscle activations. If any of these characteristics are associated with a non-linear force-length curve, then it may not be appropriate to use the spring-mass model and a single constant value of stiffness to characterise running.

Researchers have used the assumption of a linear force-length relationship [1-3, 8] and the spring-mass model to calculate stiffness and characterise running [4, 7, 9]. However, this assumption of linearity is not typically investigated. If the force-length curve deviates substantially from a linear behaviour, then use of the spring-mass model, and/or a single constant value of stiffness, may not be appropriate. While the spring-mass model has been adapted and modified to enable better predictions of experimental data [1, 15-20], there are minimal data describing whether the assumption of linearity is appropriate across a typical group of runners. Therefore, the primary aim of this investigation was to quantify the linearity of the force-length curve across a range of runners who exhibit a variety of different running styles. We hypothesised that there would be a large degree of variability in the linearity of the force-length curve, with at least 50 % of participants exhibiting clear nonlinearity. A secondary objective was to explore the association between force-length linearity and foot-strike index and speed. We hypothesised that there would be a relationship between force-length linearity and both foot-strike index and speed.

Methods

Experimental kinematic and kinetic data were collected from 28 runners (12 female) who demonstrated a range of foot-strike patterns. The mean (SD) age was 28 (4) years, height 1.75 (0.93) m and weight 62.9 (9.1) kg. Participants 10 km personal best times ranged from 29 min 30 s to 46 min 30 s (mean (SD): 37 min 36s (5 min 47 s)) and average weekly mileage from 10 to 80 miles (mean (SD): 39.75 (19.05) miles). Signed informed consent was obtained from each participant before testing, and the research was approved by the Local Ethics Committee.

Each participant ran over-ground (32 m indoor track) at four different speeds (3.3, 3.9, 4.8 and 5.6 ms^{-1}), which were chosen to be representative of typical running speeds across both recreational runners and high-performance runners [21]. Three-dimensional kinematic and kinetic data were collected using a 12-camera Qualisys Pro-reflex system (240 Hz) and 3 AMTI force plates (1200 Hz) embedded in the track. All participants wore their own running shoes, all of which were of a standard design, with no participants wearing minimal running shoes. Running speeds were measured and controlled using optical timing gates.

For this investigation, reflective markers were attached to the anterior superior iliac spines (ASIS) and posterior superior iliac spines (PSIS), as well as the lateral and medial epicondyles, 1st, 2nd, and 5th metatarsals and the heel calcaneus of the right lower limb. A rigid cluster with four markers was also attached to the thigh. Raw marker data were low pass filtered (10 Hz). Kinematic and kinetic data were analysed using Visual 3D (C-Motion, Inc., Germantown, MS, USA). The pelvis was defined using a CODA pelvis, with the hip joint centre (HJC), taken as the proximal end of the thigh, approximated using the Bell & Brand regression equations [22, 23]. Following data collection, stance phase was identified using the vertical GRF data, with a cut-off threshold of 20 N. Kinematic and kinetic data were then interpolated to 101 data points, representative of 0–100 % of the stance phase, and averaged across all trials performed by that participant (typically 7-10). HJC position, foot-strike index, CoP and GRF data were then exported to MATLAB (R2016a, The MathWorks, Inc., MA, USA).

Individual force-length curves were determined for each participant at each speed. All mass was assumed to be acting at the HJC. To determine the component of the GRF acting through the spring, F_{limb}, the resultant GRF was first determined and then projected onto the limb axis (Figure 1; Eq. 1 and Eq. 2). F_{limb} was then normalised to body mass. Lower limb length was defined as the distance from the instantaneous HJC to the average CoP, normalised to limb length.

$$F_{limb} = GRF * \cos(\theta_d) \qquad \text{Eq. 1}$$

$$\theta_d = \theta_{GRF} - \theta_0 \qquad \text{Eq. 2}$$

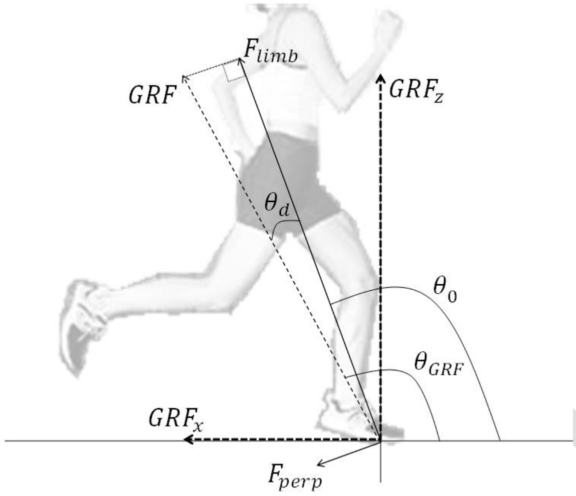

Figure 1 - Lower limb force from GRF, where θ_d represents the difference between the resultant angle of the GRFs, θ_{GRF}, and the approach angle, θ_0. The lower limb force, F_{limb}, is then determined by projecting the resultant GRF onto the lower limb axis.

To quantify linearity of the force-length curve the square of the Pearson correlation coefficient, R^2, was calculated. However, rather than calculating the R^2 value associated with the line of best fit, the calculation was modified so that an R^2 value was derived for the perfectly elastic line. This perfect elastic line was defined between the point corresponding to initial contact and midstance (point of maximum compression). During the final 8(3) % of stance, the "spring" extended beyond the resting length, likely due to the ankle plantarflexing as load reduces prior to toe-off, and consistently showed a similar and much lower gradient across participants. Therefore, the final 8(3) % of stance was not considered in the quantification of linearity.

In running literature, three primary foot-strike patterns (forefoot, midfoot and rearfoot) have been used to describe how the foot contacts the ground [24, 25]. The foot-strike index can be classified on a continuum of from 0 to 100 % based on force plate measurements [24]. In this study, the foot-strike index was calculated using the centre of pressure (CoP) and the virtual foot (defined by projecting the heel and 2nd metatarsal markers onto the floor) [24]. A foot-strike index between 0 and 33 % indicated a rearfoot strike pattern, between 34 % and 66 % indicated a midfoot strike pattern and between 67 % and 100 % indicated a forefoot strike pattern.

To address our primary objective, focused on describing the typical variation of force-length linearity across the cohort, we analysed the distribution of linearity (R^2) at the four speeds. As linearity increases the R^2 statistic will tend to one. Therefore, we defined a threshold of $R^2 \geq 0.95$ as indicating linear behaviour; above this threshold 95 % of the variance in force can be explained by changes in length. As force and length were normalised to body mass and limb length [26], respectively, the use of R^2 enabled comparison of linearity across different individuals.

To determine if there was an association between force-length linearity and foot-strike index and/or between force-length linearity and speed, a linear mixed-effects analysis was performed using R [27] and the lme4 package [28]. A single model was constructed to investigate the dependence of linearity (R^2) on both foot-strike index and speed. With this model, foot-strike index and speed were continuous variables and defined as the fixed effects, and subject was included as a random effect.

This random intercept model accounts for baseline differences in linearity for each subject. No deviations from homoscedasticity or normality were seen in the residual plots, and p-values were obtained by likelihood ratio tests of two models one with and one without the fixed effect of interest, namely foot-strike index or speed.

Results

Across the cohort of 28 runners, there was variability in the shape of the force-length curves. This variability led to a spread of R^2 values at each of the four different speeds (Figure 2). Example data from participants, exhibiting either linear (Figure 2A & 2B) or non-linear (Figure 2C - 2F) force-length behaviour during the loading phase are shown in Figure 2. Distributions of linearity (R^2) for the loading and unloading phase of stance, at each of the four speeds, are shown in Figure 3 and Table 1. These data can be interpreted using the example force-length curves shown in Figure 2 which illustrates the most linear (Figure 2A, R^2=0.995), the least linear (Figure 2F, R^2=0.476) along with four intermediary linearities at a speed of 4.8 ms^{-1}. Using the threshold of $R^2 \geq 0.95$, only 39, 46, 36 and 36 % of participants demonstrated linear behaviour at speeds 1, 2, 3 and 4, respectively, during the loading phase. However, at all speeds, the linearity of the unloading phase was, on average, greater than 0.95 (Table 1).

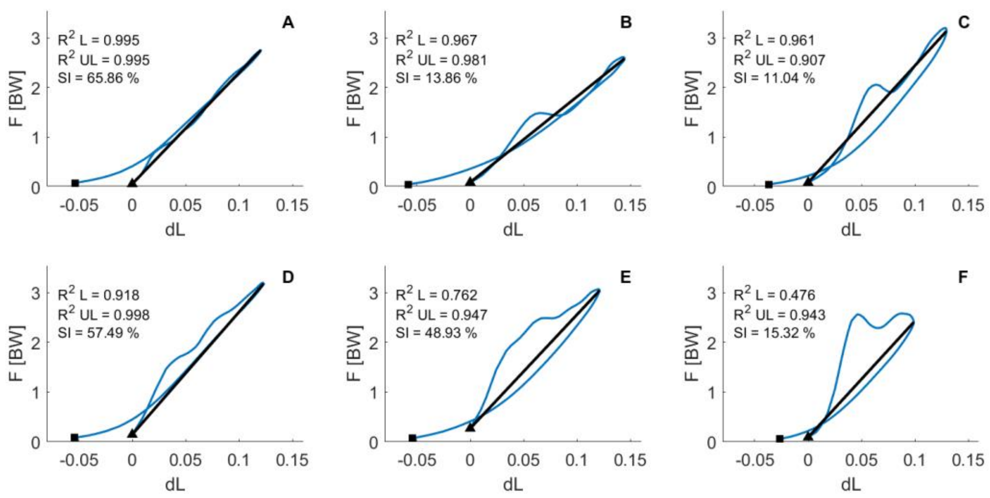

Figure 2 – Force-length curves for six participants at speed 3 (4.8 ms^{-1}) showing an example of the variation in linearity (R^2). L indicates the loading phase, UL the unloading phase, SI is the foot-strike index, F is force normalised to body mass, and dL is change in length, normalised to limb length and is therefore dimensionless. The triangle indicates the start of the loading phase and the square indicates the end of the unloading phase.

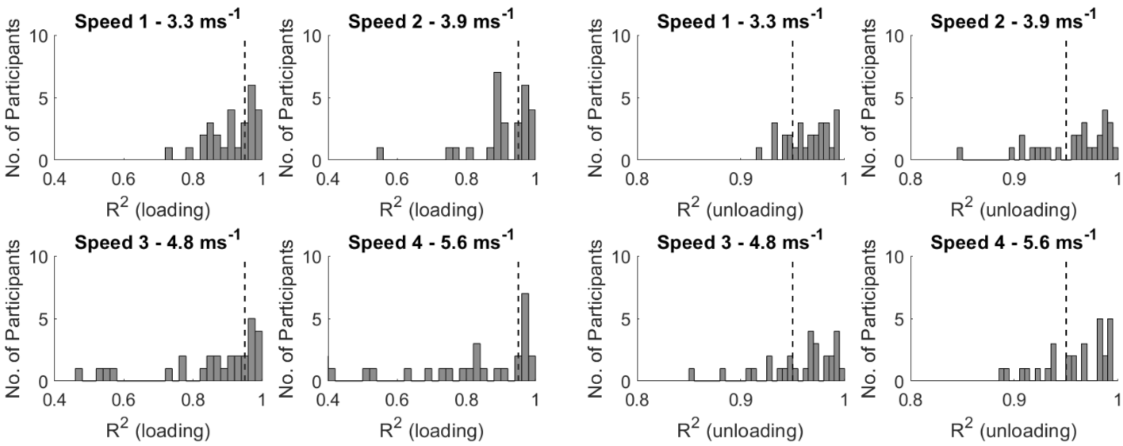

Figure 3 - Distribution of linearity (quantified using R^2 (for the loading (left) and unloading (right) phases of stance)) across the cohort of 28 runners at each of the four speeds. The threshold of $R^2 \geq 0.95$ indicating linear behaviour is shown by the vertical dashed line.

The linear mixed effect model and likelihood ratio tests showed that foot-strike index had a significant effect on linearity (R^2) of the force-length curve. These effects were observed for the loading phase (F(1) = 9.05, p = 0.003), but not the unloading phase (F(1) = 1.3, p = 0.261). However, despite the linear relationship, there was still variability in R^2 across the groups defined as either rearfoot strikers or forefoot strikers (Table 2). For example, Figure 2A and Figure 2E illustrate force-length curves for two participants with similar foot-strike indices (approximately 65 %) but who exhibited very different force-length dependence.

The linear mixed effect model and likelihood ratio tests showed that speed had a significant effect on linearity (R^2) of the force-length curve. These effects were observed for the loading phase (F(1) = 36.87, p < 0.001, respectively), but not the unloading phase (F(1) = 1.36, p = 0.244, respectively). Furthermore, although the linearity appeared to decrease as speed increased for the loading phase, linearity remained relatively constant for the unloading phase (Table 1). It is worth noting that the distribution of foot-strike indices of the 28 participants in the study showed a continuum which varied with speed (Table 2). In addition, some participants transitioned from a more rearfoot strike pattern (lower foot-strike index) at slower speeds to a more forefoot strike pattern (higher foot-strike index) at faster speeds (Table 2).

Table 1 – Mean (SD) linearity (R^2) for the loading and unloaded phases of stance across the cohort at each of the four speeds.

	SPEED 1: 3.3 ms^{-1}	**SPEED 2: 3.9 ms^{-1}**	**SPEED 3: 4.8 ms^{-1}**	**SPEED 4: 5.6 ms^{-1}**
LOADING	0.914 (0.068)	0.905 (0.095)	0.855 (0.153)	0.796 (0.208)
UN LOADING	0.965 (0.022)	0.956 (0.037)	0.957 (0.036)	0.958 (0.032)

Table 2 – Mean (SD) and range in linearity (R^2) for the loading phase of stance for participants grouped according to foot-strike pattern. n is the number of participants who adopted that foot-strike pattern at that speed, and SI is the foot-strike index.

		SPEED 1: 3.3 ms^{-1}	**SPEED 2: 3.9 ms^{-1}**	**SPEED 3: 4.8 ms^{-1}**	**SPEED 4: 5.6 ms^{-1}**
REARFOOT SI: 0 – 33%	Mean (SD)	0.900 (0.054)	0.869 (0.109)	0.766 (0.188)	0.619 (0.269)
	Range	0.792 – 0.965	0.543 - 0.977	0.476 - 0.967	0.311 – 0.75
	n	16	16	12	9
MIDFOOT SI: 34 – 66%	Mean (SD)	0.894 (0.102)	0.939 (0.047)	0.908 (0.092)	0.890 (0.090)
	Range	0.730 – 0.993	0.888 – 0.992	0.762 – 0.995	0.732 – 0.988
	n	6	6	9	12
FOREFOOT SI: 67 – 100%	Mean (SD)	0.971 (0.022)	0.970 (0.017)	0.937 (0.037)	0.862 (0.112)
	Range	0.930 – 0.992	0.957 – 0.992	0.876 – 0.984	0.690 – 0.987
	n	6	6	7	7

Discussion

Our data from 28 participants showed a wide range of force-length characteristics. Importantly, in line with our original hypotheses, less than 50 % of participants demonstrated a linear force-length at each of the four speeds. Moreover, linearity decreased as foot-strike index decreased and also as speed increased. Taken together, these findings indicate that the assumption of a linear force-length relationship is not appropriate for all runners. This is important as many previous studies have used the spring-mass model and/or a single constant value of "leg stiffness" to investigate running; however, the linearity of the force-length curve is not usually examined in the population under study.

Morin, Samozino 2007 [7] used the spring-mass model to investigate the effects of altering step frequency and contact time on leg stiffness during running. Although they found that contact time was the primary contributor to changes in leg stiffness, the authors did not comment on whether the assumption of a linear force-length curve was valid for this group of runners. In another study, Morin, Dalleau 2005 [29] reported differences in leg stiffnesses between elite middle-distance runners and physical education students. They concluded that the observed difference was a result of the different running abilities of the participants, however, they did not report on force-length characteristics. When considered in the context our findings, it is possible that these differences were the result of differences in the force-length curves and it is therefore unclear whether a single value of stiffness would be the most appropriate way to characterise differences in running style.

Our analysis showed a significant effect of foot-strike index on the degree of linearity. In general, rearfoot strikers were less likely to exhibit a linear force-length relationship. Nevertheless, some forefoot strikers did exhibit a clear non-linear force-length curve. This finding has an implication for research which seeks to compare linearity between groups of runners and/or conditions for which there could be differences in foot-strike pattern. For example, Lussiana, Hébert-Losier 2015 [9] concluded that stiffness provided a unique and alternative way of describing the biomechanical changes that occur during different running conditions [9]. However, it has previously been shown that minimal shoes sometimes result in participants transitioning from a rearfoot to a forefoot strike pattern [30], and given our findings that foot-strike index has a significant effect on linearity, their results may have been affected by the linearity of the force-length curve. This further brings into question whether it is appropriate to use a single value of stiffness to determine changes which are associated with different running conditions.

As stated previously, numerous previous researchers have assumed linear force-length behaviour to characterise lower limb stiffness during running. However, our data showed variability in the force-length characteristics for a range of foot-strike indices (Figure 2 and Figure 3) and that only 36-46 % of participants showed linear force-length behaviour ($R^2 \geq 0.95$ during the loading phase). Interestingly, as the non-linearity of the force-length curve increases, it appears to show different "phases" of stance (Figure 4); which is in close agreement with previously suggested "phases" for knee joint stiffness [31]. For example, Figure 4 shows a non-linear force-length curve broken into three (left) or four (right) "phases"; including an initial "loading" phase, one or two "transition" phases and a final "unloading" phase. These "phases" could potentially be modelled individually using the spring-mass model and would lead to multiple values of stiffness for the stance phase. This is similar to the method suggested by Hunter 2003 [15] who showed that a method which incorporated two values of stiffness predicted measured vertical GRFs more accurately than the original spring-mass model.

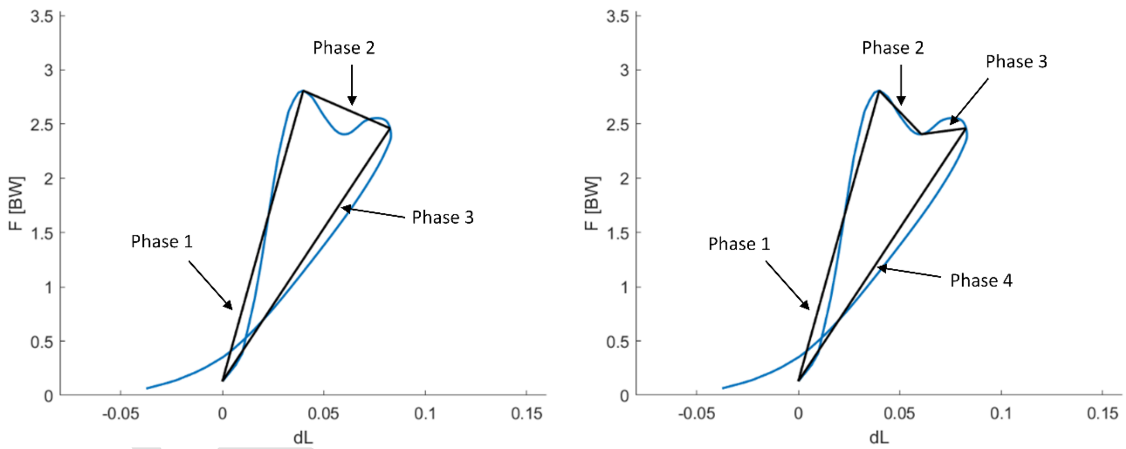

Figure 4 – The force-length curve with the lowest linearity (R^2), showing that a single value of stiffness would be inappropriate to model this curve. However, three (left) or four (right) phases may be more appropriate for curve of this shape. F is force normalised to body mass, and dL is change in length, normalised to limb length and is therefore dimensionless.

Several previous studies have sought to modify the spring-mass model to improve predictions of experimentally measured biomechanical parameters during running. These modifications, although not explicitly stated, address some of the non-linearities in the force-length relationship. For example, Hunter 2003 [15] adjusted the spring-mass model by applying a variable stiffness to improve model predictions of the vertical GRF during running. In addition, the effects of a moving point of force application (POFT) [1], multiple rigid and wobbling masses [16-19], and torsional springs [20] have also been explored. These models improved the predictions of the horizontal GRF [32], addressed the inaccuracies in modelling the impact peak in the vertical GRF [15-19] and introduced modelling of joint kinematics and kinetics [20]. However, these modifications fundamentally alter the assumptions of the spring-mass model; for example, when including a POFT the spring stiffness is no longer equivalent to leg stiffness [32], and thus emphasise that the spring-mass model, and a single constant value of stiffness, may be too simple for investigating all types of running.

There are some limitations in this study which should be acknowledged. Firstly, participants were not screened as forefoot and rearfoot strikers; however, the population included a range of runners who adopted a variety of running styles. We suggest that these data represent typical variation in force-length dependence and are an appropriate cohort to address the proposed research questions. Secondly, there is the possible influence of running ability on the linearity of the force-length relationship. The data collected for this study involved both high-performing and recreational runners [33]. However, the aim was to explore the linearity of the force-length curve for a range of foot-strike patterns and previous research has identified the presence of an impact peak in rearfoot running in both elite [13, 34] and recreational [13] runners. We suggest that the inclusion of a range of different performance levels provides insight into force-length dependence across different running styles and is therefore appropriate given the primary aim of reporting on inter-subject variability.

The data presented in this study demonstrates the variability in the force-length linearity across a cohort of runners who adopt a mix of running styles. In addition, significant associations between linearity of the force-length curve and both foot-strike index and speed were found. Given this variability, we would recommend that the force-length curve be investigated before using the spring-mass model or classifying runners using a single value of stiffness. For individuals who demonstrate non-linear force-length curves, $R^2 < 0.95$, it may be more appropriate to segment the stance phase, individually investigating the different subphases. As another alternative, future research could explore how the spring-mass model could be adapted so that it can predict non-linear force-length dependence.

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