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# An Integrative Force-Velocity-Position model applied to vertical jump

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## 1. Introduction

Force production during maximal multi-joint movements, such as jumping, is primarily influenced by the velocity and the position of the center of mass (COM) (Pommerell et al., 2025; Samozino, Morin, Hintzy, & Belli, 2010). Modeling force production as a function of these variables during multi-joint movements would provide a better understanding of the mechanisms of force production, but remains challenging. The force-velocity ( $F(v)$ ) relationship is generally well-described by a linear equation. Although the COM force-position relationship has not yet been modeled, we can assume that the force-joint angle equation proposed at the joint level (Welsh, Allen, Batliner, & Byrnes, 2015) may offer an appropriate framework to describe it, accounting for the non-linear dynamics of joint motion. Thus, the aim of this study was to investigate whether combining a linear force-velocity and quadratic force-position models could effectively characterize force production during vertical jump push-off phase.

## 2. Methods

### 2.1 Mathematical model development

$F(v)$  relationship during multijoint movements can be described by a linear function in which force depends on the theoretical maximal force ( $F_{max}$ ) and the theoretical maximal velocity ( $v_{max}$ ):

$$F(v) = F_{max} \left(1 - \frac{v}{v_{max}}\right) \quad (1)$$

Similarly, the force-position ( $F(p)$ ) relationship can be modeled by a second-order function, derived from the force-angle relationship and adapted to linear vertical movements such as vertical jumping.  $F(p)$  can then be expressed as a function of the optimal position ( $p_{opt}$ ) at which  $F_{max}$  is produced:

$$F(p) = \frac{F_{max} p}{p_{opt}} \left( \frac{-p}{p_{opt}} + 2 \right) \quad (2)$$

By combining these two equations and considering position and velocity independent (i.e.  $p_{opt}$  remains constant across velocities), the resulting model can describe force as a function of both velocity and position during multijoint movements:

$$F(v,p) = F_{max} \left(1 - \frac{v}{v_{max}}\right) \cdot \frac{p}{p_{opt}} \left( \frac{-p}{p_{opt}} + 2 \right) \quad (3)$$

### 2.2 Data collection and analysis procedures

Twelve male CrossFit athletes (age:  $26 \pm 6$  years, height:  $177.7 \pm 9.5$  cm, mass:  $81.4 \pm 11.1$  kg) performed maximal countermovement jumps (CMJs) under five randomized loading conditions: bodyweight (BW), BW + 8 kg, BW + 17 kg, BW + 40% 1RM, and BW + 70% 1RM. CMJs were executed from three push-off distances corresponding to 30–50%, 50–70%, and

70–100% of each participant's maximal squat depth (0% = standing). Maximal squat depth was defined as the vertical displacement of the COM between the lowest position reached during a maximal counter-movement (corresponding to the start position of the push-off phase) and the fully extended standing position (corresponding to take-off), which corresponds to  $p = 0$  m in our model. CMJs were separated by 2 min rest, and 3 min between loading conditions. Ground reaction forces (GRF) were recorded at 1000 Hz using two force plates (Kistler Type 9286BA, Switzerland). Vertical GRF signals were low-pass filtered at 12 Hz. COM vertical acceleration was calculated by dividing the net vertical GRF by the total system mass (body mass + external load). Vertical velocity and displacement of the center of mass were then obtained through single and double numerical integration over time.

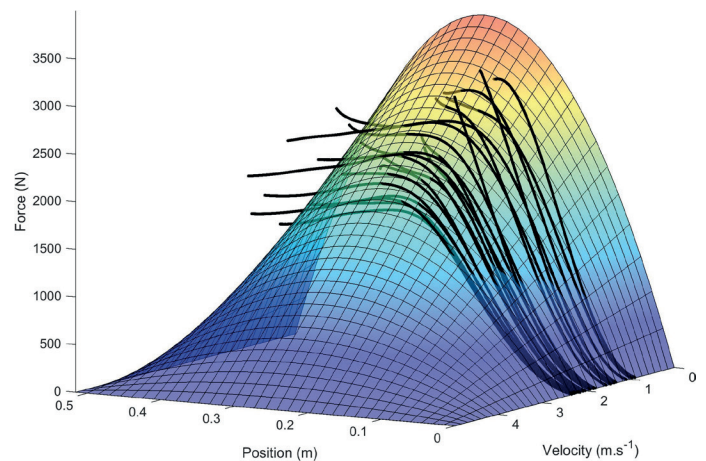
### 2.3 Model fitting and adjustment indicators

The parameters of the  $F(v,p)$  model were optimized by minimizing the squared error between the modeled and experimentally measured instantaneous force, velocity, and position data of the push-off phase, using only the 0–80% range of maximal squat depth and excluding the first 80ms of the signal to mitigate the effects of submaximal muscle activation. The coefficient of determination ( $R^2$ ) was used to assess the goodness of fit, indicating the extent to which the model accurately represents the experimental data. Additionally, the root mean square error (RMSE) was computed to evaluate the discrepancy between the modeled and experimentally measured force, velocity, and position data for the  $F(v,p)$  model. A visual inspection of the relative and mean error for specific velocity and position values was also performed to identify any systematic errors associated with particular positions.

## 3. Results and discussion

The  $F(v,p)$  model predicted average parameters of  $F_{max} = 3805 \pm 622$  N,  $v_{max} = 4.40 \pm 0.55$  m·s<sup>-1</sup> and  $p_{opt} = 0.23 \pm 0.03$  m. Regarding to goodness of fit, results revealed an average  $R^2$  of  $0.87 \pm 0.03$ , indicating a strong alignment of the model's estimation with the experimental data. The RMSE was  $280 \pm 52$  N, corresponding to a mean error of  $7.37 \pm 1.37\%$  of  $F_{max}$ , reflecting a good descriptive capacity. Visual inspection through heatmaps revealed the majority of errors occurred in the extreme positions (80%-100% of maximal squat

depth), suggesting that the model performs optimally in the 0-80% range of maximal squat depth. This reduced accuracy in the 80%-100% range of the maximal squat depth may stem from distinct force production kinetics in these deep positions, where neuromuscular coordination and muscle synergies are likely altered. Moreover, the symmetric nature of the quadratic  $F(p)$  function may not capture the asymmetric behavior of force generation specific to the 80%-100% range of the maximal squat depth. Furthermore, the  $F(v,p)$  model demonstrated a consistent fitting pattern across all participants, showing similar trends in both the force-velocity and force-position relationships during the push-off phase of the jump. Figure 1 illustrates the fit of the  $F(v,p)$  model to experimental instantaneous COM force, velocity and position data during the push-off phase of a typical subject.



**Figure 1.**  $F(v,p)$  fitting for a typical subject. Black lines correspond to instantaneous force, velocity and position measurements.

## 4. Conclusions

This study highlights that a  $F(v,p)$  model, combining linear force-velocity and quadratic force-position equations, accurately characterizes force production during the push-off phase of vertical jumping within the 0–80% range of the maximal squat depth, using three interpretable parameters. Modeling the  $F(v,p)$  relationship provides a better understanding of individual force production capabilities, yielding valuable insights for evaluation, training, and performance optimization. Future research should explore the sensitivity of the  $F(v,p)$  relationship to training and examine whether alternative model combinations could improve overall movement modeling.

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## Conflict of Interest Statement

None.

## Contributor Roles

FP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Resources, Validation, Visualization, Writing- original draft, Writing-review & editing ; SB: Conceptualization, Data curation, Formal analysis, Supervision, Validation, Visualization, Writing-original draft, Writing-review & editing; AR: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing-review & editing; PS: Conceptualization, Methodology, Resources, Supervision, Validation, Writing-review & editing; JB: Conceptualization, Methodology, Resources, Supervision, Validation, Writing-review & editing; BM: Conceptualization, Data curation, Formal analysis, Software, Resources, Supervision, Visualization, Writing-review & editing; NP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing-review & editing.

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