PREDICTING GROUND REACTION FORCES FROM TRUNK KINEMATICS: A MASS-SPRING-DAMPER MODEL APPROACH

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The purpose of this study was to explore if a mass-spring-damper model can simulate trunk kinematics during running with the purpose of predicting ground reaction forces (GRF). Vertical GRF and trunk kinematics was measured for 16 participants during running at 2-5 m·s^{-1}. The vertical trunk acceleration were used to simulate the acceleration of a mass-spring-damper model's upper mass and generate the eight model parameters required to predict GRF. Mean squared errors between 0.8 ± 0.4 and 0.9 ± 0.5 m·s^{-2} and between 19.1 ± 7.0 and 27.9 ± 14.5 N·kg^{-1} were observed for the trunk acceleration and GRF respectively. Despite excellent trunk acceleration simulations, poor GRF predictions indicated that a simple mass-spring-damper model is shortcoming to predict variations in distinct loading features across different running speeds.

KEY WORDS: Running, Trunk acceleration, Spring-mass model, Mechanical load.

INTRODUCTION: Human running is spring-like in nature as the elastic tissues of the support leg absorb and return elastic energy. Simple spring-mass models have therefore been used successfully to estimate the vertical displacement and lower limb stiffness of humans during running (Blickhan, 1989). In this approach the vertical ground reaction force (GRF) acting on the model is estimated as a half-sine wave. It is however well-known that the body is exposed to high-frequency impact forces during running when the foot collides with the ground (Bobbert et al., 1991), generating an initial impact peak in the GRF pattern which is neglected in the simple spring-mass model approach.
A modified mass-spring-damper model (MSD-model) has been successful in replicating measured GRF including both the initial impact peak and the active peak related to the displacement of the body's centre of mass (Derrick et al., 2000; Nedergaard et al., Under review). Measured GRF has traditionally been used to simulate the motion of the MSD-model and as a consequence its application in field settings is limited. The aim of this study was to explore if a MSD-model can simulate vertical trunk kinematics during running, with the purpose of predicting GRF.

METHODS: Sixteen participants (age 22 ± 3 years, height 177 ± 8 cm, mass 74 ± 9 kg) were asked to complete 4 running trials at 2, 3, 4 and 5 m·s^{-1} (± 5%) in a randomised order. Approach speed was measured with photocell timing gates (Brower Timing System, Draper, UT, USA) that were placed 2 m apart and 2 m from the center of a force platform. Participants were instructed to run over the force platform with their dominant leg.
Vertical ground reaction forces ($GRF_{measured}$) were measured with a Kistler (9287C, Kistler Instruments Ltd., Winterhur, Switzerland) force platform sampling at 3000 Hz. Three-dimensional trunk kinematics were simultaneously recorded in Qualisys Track Manager (Qualisys AB, Gothenburg, Sweden) with 10 optoelectronic cameras (Qualisys AB, Gothenburg, Sweden) sampling at 500 Hz. The trunk segment was defined from a static trial as described in Vanrenterghem et al. (2010) with spherical reflective markers positioned at C7, Sternum, Xiphoid process and T8 to track the movements of the trunk segment. GRF and marker data were filtered with a 4th order low-pass Butterworth filter with a cut-off frequency at 20 and 10 Hz, respectively. Touch-down and toe-off events were created when $GRF_{measured}$ crossed a 20 N threshold and the vertical trunk acceleration ($TrunkAcc_{measured}$) was calculated as the second time derivative of the vertical trunk displacement. Data processing was done using Visual3D (C-motion, Germantown, MD, USA).

A mass-spring-damper model (MSD-model) consisting of a lower mass (m_2) on top of a spring-damper system representing the support leg at initial impact, and an upper mass (m_1) on top of another spring representing the rest of the body (Figure 1), were used to model the multi-segment dynamics of the participant's body (Derrick et al., 2000; Nedergaard et al., *under review*). The GRF acting on the MSD-model (GRF_{model}) was solved numerically from the equation of motion of the two masses (Equations 1-3) from eight initial model parameters: the position (p_1) and velocity (v_1) of the upper mass, the position (p_2) and velocity (v_2) of the lower mass, the mass ratio (λ) of the lower mass relative to the participant's total body mass, the natural frequency of the upper (ω_1^2) and lower spring (ω_2^2), and the dampening ratio (ζ) of the damper.

$$a_1(t) = -\omega_1^2(p_1 - p_2) + g \qquad \text{[Equation 1]}$$
$$a_2(t) = -\omega_2^2 p_2 + \omega_1^2\lambda(p_1 - p_2) - 2\zeta\omega_2 v_2 + g \qquad \text{[Equation 2]}$$
$$GRF_{model} = \frac{M\omega_2}{1+\lambda}(\omega_2 p_2 + 2\zeta v_2) \qquad \text{[Equation 3]}$$

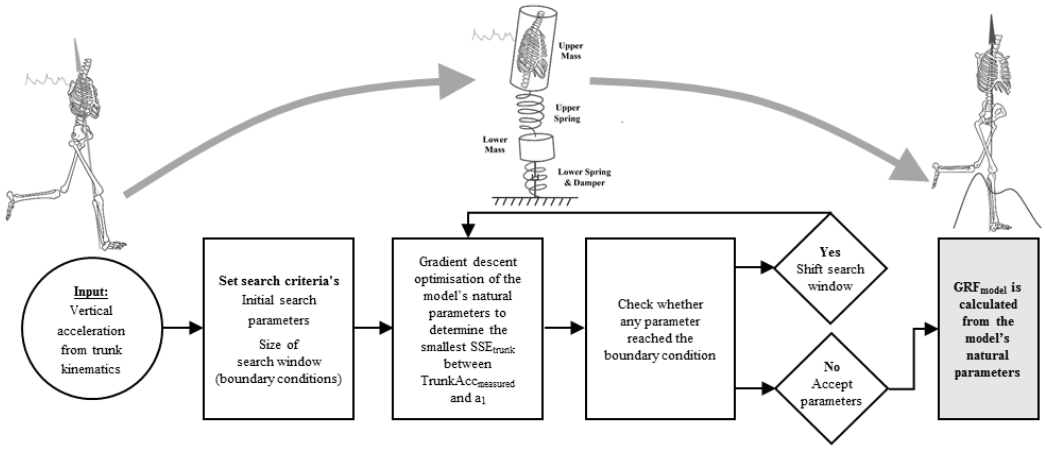

Figure 1: Illustration of the MSD-model approach and a flow-chart of the optimisation routine.

The eight initial model parameters were obtained from a purpose built gradient descent optimisation routine in Matlab (The MathWorks, Inc., Natick, MA, USA) where the upper mass acceleration (a_1) was simulated from $TrunkAcc_{measured}$. The sum of squared errors between the $TrunkAcc_{measured}$ and a_1 was used to determine the eight model parameters from which the MSD-model best simulated $TrunkAcc_{measured}$ for the individual trials. The two second order differential equations (Equations 1 and 2) were then transformed to four first order differential equations and solved numerically using a 4th order Runge Kutta method to calculate GRF_{model} from the eight model parameters.
$GRF_{measured}$ and GRF_{model} were normalised to the participant's mass and the mean squared errors (MSE) were calculated for both GRF and the trunk. The MSD-models ability to predict the following GRF loading characteristics was evaluated: Impulse, Impact Peak (peak from 0-25% of stance) and Active Peak (peak from 25-75% of stance). These GRF variables were averaged per condition for each individual participant and Bland-Altman analyses were used to explore the within condition mean differences (bias) and 95% limits of agreement (LoA) between the GRF loading variables calculated from $GRF_{measued}$ and GRF_{model} (Bland and Altman, 2010).

RESULTS: The MSD-model was able to simulate the acceleration pattern of $TrunkAcc_{measured}$ with very high accuracy (average MSE between 0.8 ± 0.4 and 0.9 ± 0.5 $m \cdot s^{-2}$) across the different approach speeds (Table 1). Despite the very good match between a_1 and $TrunkAcc_{measured}$, poor GRF predictions (average MSE between 19.1 ± 7.0 and 27.9 ± 14.5 $N \cdot kg^{-1}$) were obtained from the MSD-model regardless of approach speed (Figure 2).

Table 1
Within condition mean squared error (mean ± SD)

MSE	2 m·s^{-1}	4 m·s^{-1}	5 m·s^{-1}
Trunk (m·s^{-2})	0.9 ± 0.5	0.9 ± 0.5	0.8 ± 0.4
GRF (N·kg^{-1})	27.9 ± 14.5	21.3 ± 9.1	26.8 ± 9.0

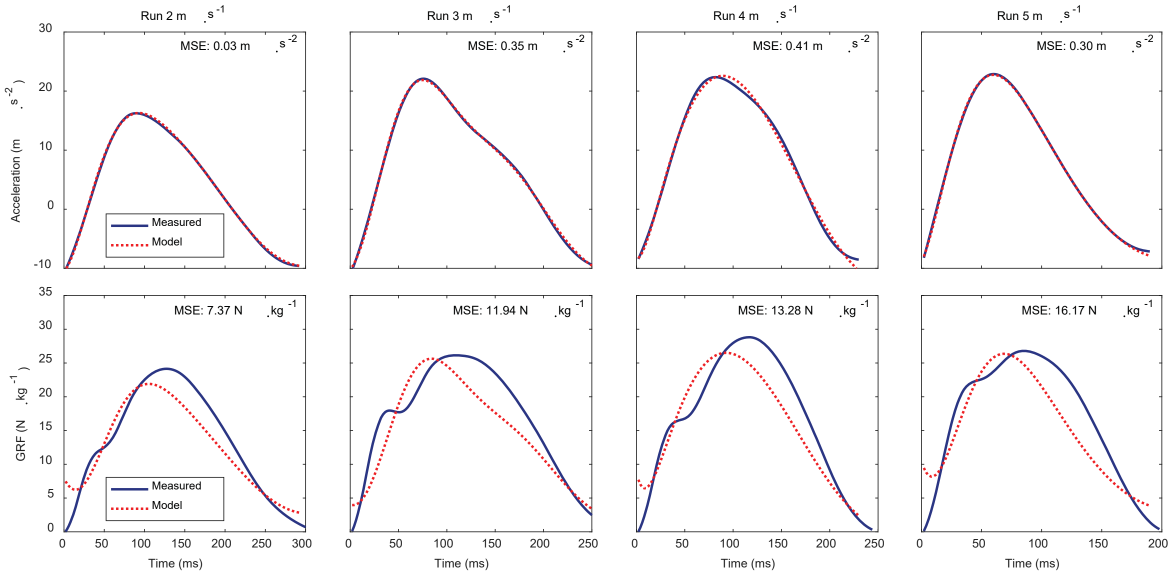

Figure 2: Representative examples of the measured and modelled acceleration and GRF.

Trials with GRF MSE values above 75 N·kg^{-1} were not included in the Bland-Altman analysis, excluding a total of 15 out of 256 trials. GRF$_{model}$ underestimated the Impulse observed for GRF$_{measured}$ (3.3 ± 0.4 and 3.9 ± 0.2 N·s·kg^{-1}) with mean bias between 0.36 and 0.40 N·s·kg^{-1} (Figure 3). Average Impact Peaks between 19.5 ± 0.4 and 24.1 ± 0.4 N·kg^{-1} were observed for GRF$_{measured}$ with mean bias between -3.9 and 1.5 N·kg^{-1}. Finally, the GRF$_{model}$ underestimated the Active Peak from GRF$_{measured}$ (23.9 ± 1.7 and 26.6 ± 2.1 N·kg^{-1}) with mean bias between 0.36 and 0.40 N·kg^{-1}. Large LoA were generally observed regardless of loading variable and approach speed.

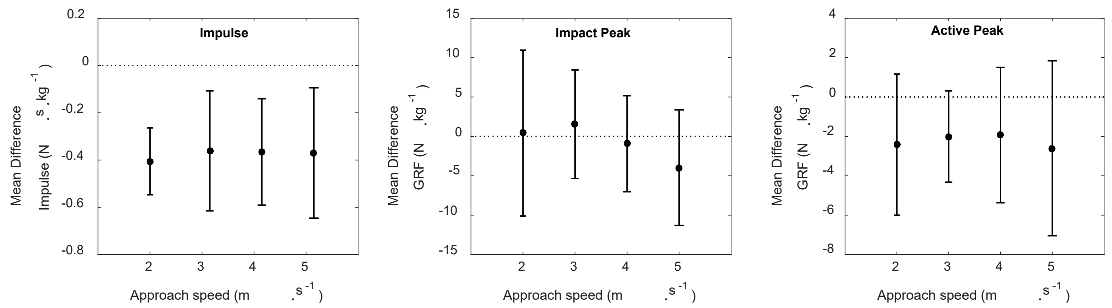

Figure 1: Results from the Bland-Altman analysis of the GRF loading characteristics, showing the mean difference (square) and 95% limits of agreements (error bar).

DISCUSSION: The aim of this study was to explore if a MSD-model can simulate vertical trunk kinematics during running with the purpose of predicting GRF. The MSD-model was able to simulate the TrunkAcc$_{measured}$ from vertical trunk kinematics with very high precision and generate the eight model parameters required to predict GRF$_{model}$. Despite the very good match between a_1 and TrunkAcc$_{measured}$, poor GRF predictions were observed across approach speeds when vertical trunk kinematics was used as model input.

The MSD-model approach introduced in this study builds on the assumption that the motion of the model's upper mass is equivalent to the motion of the trunk, in this case the vertical acceleration of the trunk. This assumption is one possible causes of the poor GRF predictions from the MSD-model since the upper mass, according to the definition in existing literature, represents the motion of the whole body apart from the support leg during running (Derrick et al., 2000). Constructing a much more complex MSD-model, including an additional spring-mass system to better present the trunk may have improved the GRF predictions, but would at the same time make the model highly complicated. It did however seem feasible to use the motion of the trunk to simulate the acceleration of the upper mass as the trunk segment represents the largest proportion of the whole-body mass (Dempster, 1955).

Despite the poor GRF prediction observed in this study when trunk kinematics is used to generate the eight model parameters required to determine GRF_{model} from MSD-models, researchers should continue to explore the opportunity of using body segment kinematics for this purpose. Especially with the potential of translating such findings to signals obtained from wireless body-worn sensors such as the accelerometers that are integrated in GPS devices for running analysis and training load monitoring in team sports (Akenhead & Nassis, 2016). This would allow researchers and practitioners to monitor the whole-body biomechanical load to which runners are exposed to, and relate these findings to soft-tissue stresses in the lower extremities.

CONCLUSION: This study showed that vertical trunk kinematics could be used as model input to generate the eight model parameters required to predict GRF from a mass-spring-damper model. Despite the successful application of vertical trunk acceleration as model input, variations in key GRF features across running speeds could not be predicted. Researchers should continue to explore the ability to estimate the multi-segment dynamics of the human body and the associated GRF during running from segmental accelerations. Ultimately, this will allow researchers and practitioners to monitor the external biomechanical load due to athlete-ground interaction in field settings and potentially provide useful information about soft-tissue adaptions from external biomechanical load during running related movements.

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