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Simulation of running impact using a viscoelastic model considering contact phase

Yoshihisa Sakurai[a]*, Takeo Maruyama[a]

[a]*Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552, Japan*

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Abstract

The purposes of this study were to develop and validate a new viscoelastic model which can consider the contact phases of running. For these purposes, a simple mechanical model of the human body including two contact points was developed. Three healthy male performed barefoot running at different speeds. The simulated values during the passive phase using this model were well estimated. It was shown that this new model may be useful to analyze the impact force during running.

Keywords: Running; Simulation; Model; Contact phase; Impact force

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1. Introduction

Impact forces during running cause injuries at the ankle, knee, and hip joint of human. It is, therefore, important to know the characteristics of human landing. Impact force, vertical ground reaction force (GRF), during running generally has two peaks: the first impact peak (passive phase) immediately after the contact between the foot and the ground and the second one (active phase). Human during impact can be considered as a mechanical system [1] so a simple mass-spring-damper model is one of the good approaches to simulate the human landing. Many researches, therefore, have been done to simulate impact forces using this kind of mechanical models during landings of hopping and running [1-3].

Human being generally lands with the heel part first and pushes the ground with the toe part at the active phase of the contact during running. There are, therefore, three contact phases in a stance phase of the running; heel part contact, whole foot contact, and toe part contact. There is a research which measured the distributions of impact load during running by the force sensors [4]. Most mechanical models used in previous researches, however, have not considered this important feature of human running and use a constant mechanical property at the contact point [1-3].

The purposes of this study were to develop and validate a new viscoelastic model which can consider the three contact phases of running. The validity of the new model was verified by a comparison of the measured data.

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* Corresponding author. Tel.: +81-3-5734-2373; fax: +81-3-5734-2373.
E-mail address: sakurai.y.ac@m.titech.ac.jp

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Nomenclature

m_1	upper mass of the viscoelastic model (kg)
m_2	lower mass of the viscoelastic model (kg)
x_1	vertical displacement of the upper mass (m)
x_2	vertical displacement of the lower mass (m)
x_3	vertical displacement of the massless point (m)
k_1	spring connecting the upper mass and the lower mass (N/m)
k_2	spring connecting the upper mass and the massless point (N/m)
k_3	nonlinear spring representing the deformation of the heel part (N/m^5)
k_4	nonlinear spring representing the deformation of the toe part (N/m^5)
c_1	damper connecting the upper mass and the lower mass (Ns/m)
c_2	damper connecting the lower mass and the massless point (Ns/m)
g	gravity constant (m/s^2)
F	measured vertical GRF (N)
F_s	simulated vertical GRF (N)
F_{s_h}	simulated vertical GRF by the heel part (N)
F_{s_t}	simulated vertical GRF by the toe part (N)
TC	the timing of toe part contact with the ground (ms)
HO	the timing of heel part off from the ground (ms)
$x_3(TC)$	vertical displacement of the massless point at TC (m)
$RSEG$	the relative standard error of the vertical ground reaction force (%)
F_{p1}	the difference at the peak passive vertical GRF values (N)
F_{min}	the difference at the first local minimum values after the passive peak (N)
TF_{p1}	the difference in the time that the peak passive vertical GRF occurred (ms)
TF_{min}	the difference in the time that the minimum values occurred (ms)

Three healthy males (Age: 26.0±1.7 years; height: 1.72±0.1 m; mass: 61.3±3.2 kg) participated in this study. Subjects had no known disorders that would influence their running performances. Before the experiment, the purposes and procedure of this study were explained to each subject and then informed consents were obtained from all subjects.

Each subject performed three sets of running at self-selected normal, slow, and fast speeds along a 12-m runway with barefoot to neglect the influences of the footwear properties. The subjects were asked to run in each speed until at least five sets of clean running were recorded. Clean running means the impact lower extremity lands only one force plate.

Each subject wore 26 reflective markers on his anatomical landmarks to calculate velocities of center of mass (COM) of the whole body and each segment. Each motion was recorded using MAC 3D system (Motion Analysis Co., USA) at 200 Hz. In addition, the GRF was measured using four Kistler force plates (0.6m x 0.9m, Kistler Instrument, Inc., Switzerland) at 1000 Hz synchronized with the MAC 3D system.

2.2. Data processing

The stance phase was defined using 5N threshold from the raw vertical GRF of the contact force plate. Motion data and GRF data were smoothed by a weighted average. Motion data were transferred to 1000 Hz using the spline interpolation. The Japanese body segment inertia parameters [5] were used to define each segment and calculate the COM of the whole body.

TC was defined using the vertical velocity of the toe marker. After the heel contact, the vertical toe velocity toward the ground increased due to the plantar flexion and began to decrease because of the toe part contact with the ground. The timing of the maximum vertical toe velocity toward the ground was, therefore, used as TC. HO was assumed that the timing of the direction change of the shear force because it was impossible to define HO using marker data. As a result, the stance phase was divided into three phases: from the landing to TC (phase 1), from TC to HO (phase 2), and from HO to the takeoff (phase 3).

2.3. Model

The viscoelastic model (Fig. 1(a)) proposed by Miyaji and Kobayashi [6] was used as a basic model. This model consists of two masses, two linear springs, two linear dampers, and a nonlinear spring at the contact point. The equations of motions (EOM) are expressed as follows:

$$m_1\ddot{x}_1 = -k_1(x_1 - x_2) - c_1(\dot{x}_1 - \dot{x}_2) - m_1 g \tag{1}$$

$$m_2\ddot{x}_2 = -k_2(x_2 - x_3) - c_1(\dot{x}_2 - \dot{x}_3) - m_1(\ddot{x}_1 + g) - m_2 g \tag{2}$$

$$-k_3 x_3^{\,5} = -k_2(x_2 - x_3) - c_1(\dot{x}_2 - \dot{x}_3) \tag{3}$$

2.3.1. Phase 1

During phase 1, the basic model was used to simulate vertical GRF. In this model, nonlinear spring represents the deformation of the heel part. The vertical GRF is calculated by following equation:

$$F_S = F_{S\_h} = -k_3 x_3^{\,5} + 5 \tag{4}$$

The threshold of 5N was used to define contact phase, so the simulated vertical GRF was added 5N.

2.3.2. Phase 2

A modified model (Fig.1 (b)) which has two nonlinear springs representing the toe and heel parts was used to represent phase 2. Only Eq. (3) was modified from the basic model in the EOM and was written as

$$-k_3 x_3^{\,5} - k_4 g(t)^5 = -k_2(x_2 - x_3) - c_1(\dot{x}_2 - \dot{x}_3) \tag{5}$$

The Eq. (5) and (6) showed that the natural length of the nonlinear spring of the toe part was a time function. The vertical GRF was calculated by following equation:

$$F_S = F_{S\_h} + F_{S\_t} + 5 = -k_3 x_3^{\;5} - k_4 g(t)^5 + 5 \tag{7}$$

$$F_{S\_h} = -k_3 x_3^{\;5} \tag{8}$$

$$F_{S\_t} = -k_4 g(t)^5 \tag{9}$$

2.3.3. Phase 3

In phase 3, only the toe part contacted with the ground instead of the heel part, so k_4 is used in place of k_3 in the basic model (Fig.1 (a)). In the EOM, Eq. (3) was changed and expressed as

$$-k_4 x_4^{\;5} = -k_2(x_2 - x_3) - c_1(\dot{x}_2 - \dot{x}_3) \tag{10}$$

The simulated vertical GRF was also modified from Eq. (4) and given by

$$F_S = F_{S\_t} = -k_4 x_4^{\;5} + 5 \tag{11}$$

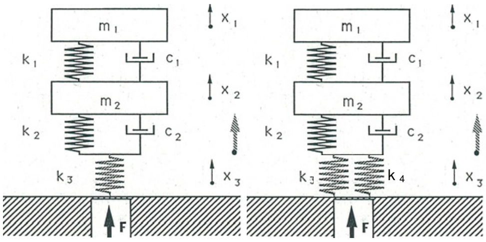

Fig. 1. (a)Schematics of the basic viscoelastic model [6]; (b) Schematics of the viscoelastic model during phase 2

2.4. Simulation

As this model included only passive elements and did not include active components such as actuator, it can be used to simulate only passive phase [1, 2]. The simulations were, therefore, carried out during the eccentric phase in this study. The eccentric phase corresponded to the duration from the impact to the minimal value of the COM displacement which was calculated by the measured vertical GRF in this study.

The differential equations were defined by each EOM during each phase. These equations were solved using 'ode45' function (MATLAB) which used a fourth and fifth order Runge-Kutta numerical integration routine with a time step of 1ms. Initial values of displacement (x_1 , x_2 , x_3) were both given 0 and those of velocity (v_1 , v_2) were calculated by measured velocity of each segment at the moment of the impact.

The minimum value of the objective function (OF) was found by the optimizing routine using 'fminsearch' function (MATLAB). The OF included timing and magnitude terms [3] to simulate the passive phase more accurate and was defined as

$$OF = RSEG + |F_{p1}| * 0.1 + |F_{min}| * 0.05 + |TF_{p1}| * 10 + |TF_{min}| * 5 \tag{12}$$

3. Results and discussions

There was measurement error in two out of 45 trials so 43 trials were analyzed. Table1 shows the running velocities of all conditions for each subject. There is a significant difference of running velocity in each condition.

Table 1. Running velocities (mean ± SD) of all conditions.

Subject	Slow (m/s)	Normal (m/s)	Fast (m/s)
A	3.0 ± 0.1	3.8 ± 0.1	4.6 ± 0.3
B	2.8 ± 0.2	3.3 ± 0.3	4.0 ± 0.0
C	3.6 ± 0.0	4.1 ± 0.1	4.8 ± 0.1

Fig. 2(a) shows typical measured and simulated vertical GRFs. The vertical GRF of passive phase was simulated well using the new model. The accuracy is, however, not good after passive phase and new model underestimates the impact force during the active phase. This phenomenon happens in most trials and is in agreement with results of previous study [3]. This implies that this model needs actuator force from about 60 ms after landing in this trial (Fig. 2(a)). Fig. 2(b) depicts typical simulated vertical GRF by the heel and the toe parts. These time histories show the similar results of previous study [4] measured by force sensors.

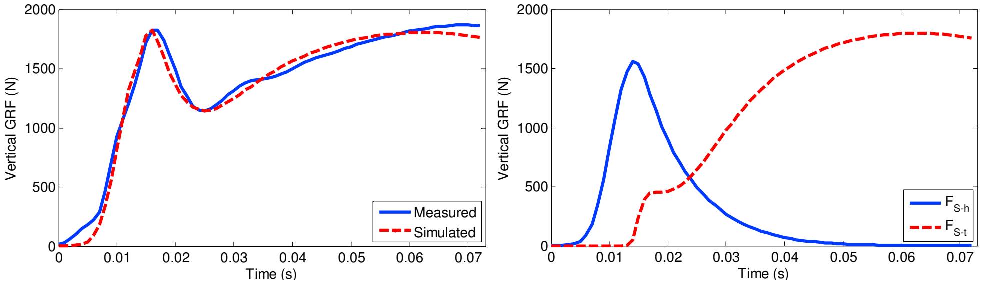

Fig. 2. (a)Typical measured and simulated vertical GRF; (b) typical simulated vertical GRF by the toe part (F_{s_h}) and heel part (F_{s_t}) of Subject B's normal running. In this trial, TC was 13 ms and the simulation duration was from the impact to the 73 ms after impact

Table 2 shows the values of OF terms for each subject. The values of OF terms except for RSEG were considerably small. This indicated that this method could simulate the vertical GRF of the passive phase very accurate. On the other hand, the RSEG values of subject A and C were higher than those of subject B. There is only one local minimum between the passive and active peaks in an ideal vertical GRF like Fig. 2 (a). Most of vertical GRFs of subject A and C, however, had a plateau phase or several local minimums in this phase. After local minimum, simulated vertical GRF kept on increasing toward the peak of active phase, but measured one did not. Moreover, the coefficients of OF (Eq. (12)) were set as RSEG was less sensitive.

In Fig. 2(b), the toe part began to contact with the ground before the passive phase peak. The simulated vertical GRF (Fig. 2(a)) at this peak should be influenced a little by the toe part force. Hence, this model would be useful to investigate the impact force more precisely through further research such as the sensitivity analysis. There are, however, some limitations in this model. As mentioned above, this model is effective only for the passive phase.

Subject	RSEG (%)	$\lvert TF_{p1}\rvert$ (ms)	$\lvert TF_{min}\rvert$ (ms)	$\lvert F_{p1}\rvert$ (N)	$\lvert F_{min}\rvert$ (N)
A (n = 15)	16.4 ± 3.2	0.5 ± 0.7	0.7 ± 0.9	0.1 ± 0.3	0.3 ± 0.4
B (n = 14)	8.6 ± 2.3	0.3 ± 0.5	0.4 ± 0.6	0.0 ± 0.0	3.3 ± 9.3
C (n = 14)	22.5 ± 6.3	0.8 ± 0.8	1.3 ± 0.9	40.4 ± 71.0	84.7 ± 178.9

4. Conclusion

This study developed the new viscoelastic model which can consider contact phase during running. The validity of this was verified by comparing the simulated vertical GRF with measured one by force plates. The main result is that the new method can simulate the passive phase immediately after landing.

Acknowledgements

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