[Dynamic Waling 2020]

Estimation of 3D GRF during running from a single sacral measurement using artificial neural network.

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Background & Aim

- Motoring and analyzing GRF in running is important because it is highly related to injury. However, it is hard to measure from outside of laboratory.
- Therefore, many studies have been conducted to estimate the ground reaction force(GRF) from kinematic information to expand providing information from wearable motion monitoring device [1-2]. Recently, GRF during walking was estimated from a single sacrum-mounted IMU using spring-loaded inverted pendulum (SLIP) model and feed forward artificial neural network (FFNN) [3].
- Since running can also be interpreted as point mass dynamics (ridged dynamics or SLIP dynamics), this study proposed two methods of estimating 3-axis GRFs from sacrum kinematics based on mechanical knowledge during running.

Hypothesis

(A) Hypothesis 1 : ridged dynamics **(B) Hypothesis 2 : SLIP dynamics**

$$normalized\ \overrightarrow{\mathrm{GRF}} = \vec{a}_{\mathrm{CoM}} \approx f(\vec{a}_{\mathrm{sacrum}}) \approx \sum \left(\mathrm{W_j} * \sigma \left(\sum \mathrm{w}\vec{a}_{sacrum} + b \right) + \mathrm{B_j} \right)$$

$$normalized\ \overrightarrow{\mathrm{GRF}} = -\mathrm{k}'\Delta \mathrm{l}\vec{e} \approx g(\vec{x}_{\mathrm{sacrum}}) \approx \sum \left(\mathrm{W_j} * \sigma \left(\sum \mathrm{w}\,\vec{x}_{sacrum} + b \right) + \mathrm{B_j} \right)$$

Figure 2. Hypothesis based on running dynamics.

- There are two simple models of running. Because GRF is only external forces to CoM, GRF could be express by acceleration of CoM (Figure1. (A)) or displacement of CoM (Figure 1. (B)).
- The assumption used both hypothesis was that CoM kinematics is function of sacrum kinematics.
- By using universal approximation theorem [4], we approximated GRF in the formula of FFNN.
- Therefore we hypothesized that GRF could be estimated by using FFNN from both sacral acceleration and displacement.

Methodologies

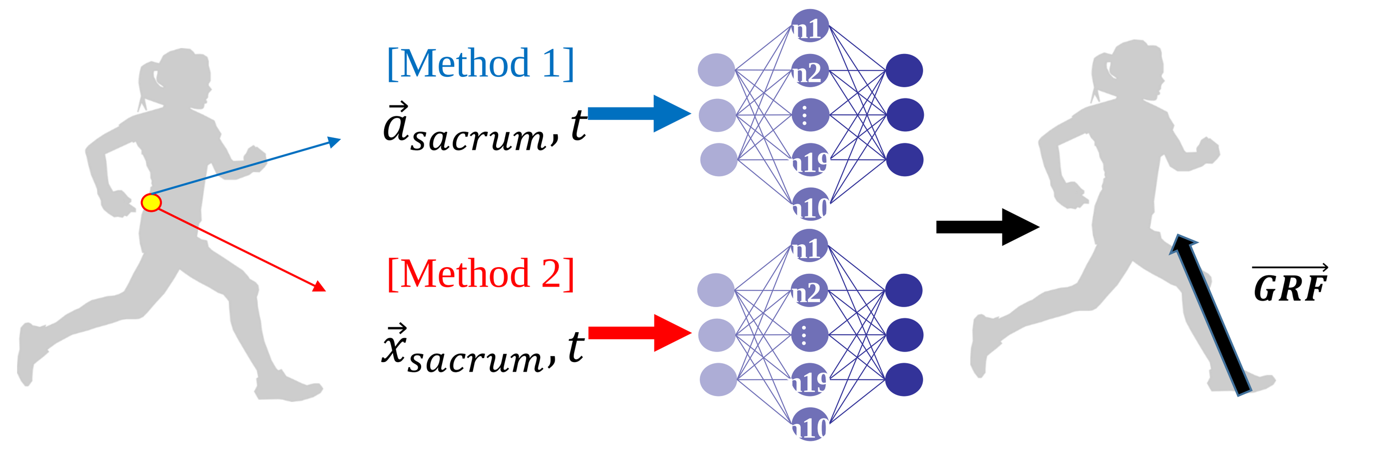

Figure 2. Schematic of proposed methods.

- Based on our hypothesis, we proposed two estimation methods, sacral kinematic data was used as an input of FFNN (Figure 2.). The time data was also used as input data following previous study [3].

Experiment and validation

- Seven young-male subjects participated in the experiment, which ran at 2.85 m / s on a treadmill with a built-in force plate. The sacral kinematic data was measured by the optical motion capture system(200Hz) and GRF was measured by force platform(400Hz). All data was filtered by Butterworth 5th zero-phase filter and cut-off frequency was 10Hz.
- The FFNN was three-layered feedforward neural network consisting of input layer, hidden layer having 10 hidden nodes, and output layer.
- To ensuring generalization of methods, leave-one-subject-out cross validation was used.
- Data processing was conducted by MATLAB2018b and machine learning process was conducted by Pytorch.

Result

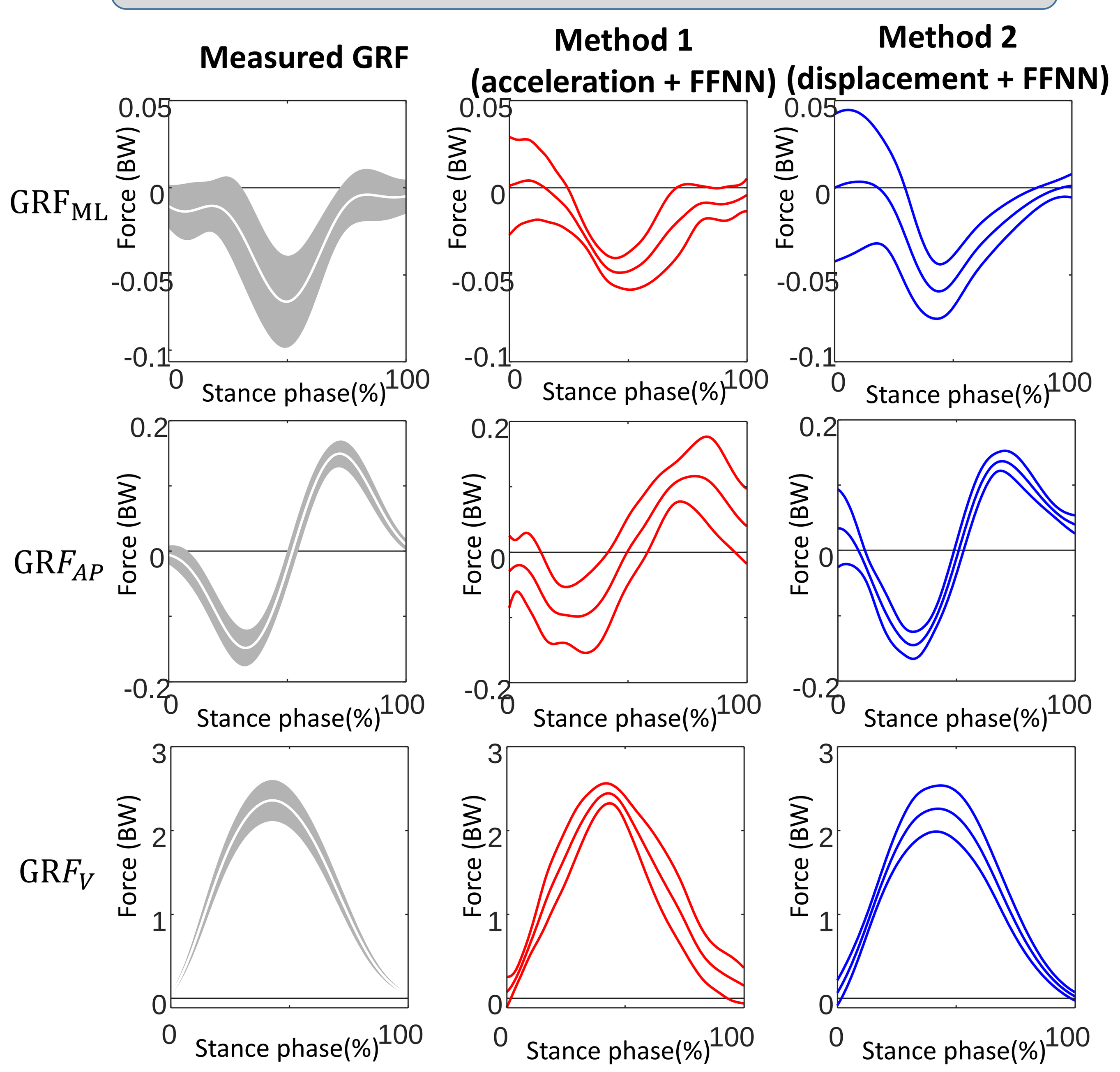

Figure 3. Measured GRFs and estimated GRFs.

Table 1. Results of estimation accuracy.

	Method 1 (acceleration + FFNN)			Method 2 (displacement + FFNN)		
	RMSE(BW)	NRMSE(%)	r	RMSE(BW)	NRMSE(%)	r
$\mathrm{GRF_{ML}}$	0.02±0.01	34.34±15.37	0.70±0.39	0.03±0.01	44.44±6.91	0.68±0.32
$\mathrm{GRF_{AP}}$	0.06±0.02	21.60±6.62	0.78±0.18	0.04±0.01	12.44±2.98	0.95±0.08
$\mathrm{GRF_{V}}$	0.28±0.12	12.25 ±5.51	0.95±0.03	0.20±0.09	8.72±4.16	0.99±0.02

- The results of estimating GRF are shown in Figure 3. and Table 1. Vertical GRF ($\mathrm{GRF_V}$) was most accurately estimated and medio-lateral GRF ($\mathrm{GRF_{ML}}$) was estimated with the lowest accuracy with both methods.
- In method 2, estimation accuracy of $\mathrm{GRF_V}$ and anteroposterior GRF($\mathrm{GRF_{AP}}$) is higher than method 1 ($p<0.05$).
- Estimation accuracy of $\mathrm{GRF_{ML}}$ in method 2 is lower than method1. However, there are no significant differences.

Discussion

- Method 2 is more accurate than method 2. Since additional acceleration caused by relative pelvic rotation motion was added to acceleration of CoM, the correlation between CoM acceleration and sacral acceleration is low [5]. Compare to acceleration, the correlation between sacral and CoM displacement is relatively higher. (Not shown in this poster)
- Compare to a previous study used convolutional neural network (CNN) model which is more complex than our FFNN, our estimation accuracy of $\mathrm{GRF_V}$ and
- The estimation accuracy of $\mathrm{GRF_{ML}}$ is poor because our methods are based on passive dynamics, although proper control should be needed in medio-lateral direction in locomotion.[6].
- There are still limitations. 1) The number of subjects was much smaller than other studies. 2) Real application issues(segmentation and integration) [3].

Conclusion

- In this study, based on point-mass dynamics in running, we estimate the 3D GRF when running through a simple FFNN from a single measurement.
- Since the GRF can also be estimated as sacrum kinematics both walking and running, it is expected to expand the information obtainable by the user from the sacrum-mounted wearable device by integrating previous research methods.

References

[1] F. J. Wouda et al., "Estimation of vertical ground reaction forces and sagittal knee kinematics during running using three inertial sensors," *Frontiers in physiology*, 2018.
[2] W. R. Johnson et al., ""Predicting athlete ground reaction forces and moments from spatio-temporal driven CNN models." *IEEE Transactions on Biomedical Engineering*, 2018.
[3] H. Lim, B. Kim, and S. Park, "Prediction of Lower Limb Kinetics and Kinematics during Walking by a Single IMU on the Lower Back Using Machine Learning", *Sensors*, 2020
[4]G. Gybenko, "Approximation by superposition of sigmoidal functions", *Mathematics of Control, Signals and Systems,* 1989
[5] R. D. Gurichiek et al. "The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks", *Journal of Biomechanics*, 2017
[6] M. Lee and S. Park, "3D dynamics of the center of mass (CoM) and ground reaction force (GRF) during walking are emulated by spring mechanics with simple foot placement control", *Manuscript submitted for publication.*

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