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Estimation of Ground Reaction Force Using Wearable Sensors for Mobile Running Monitoring System

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Presenter’s short resume

Kyoko Shibata, PhD

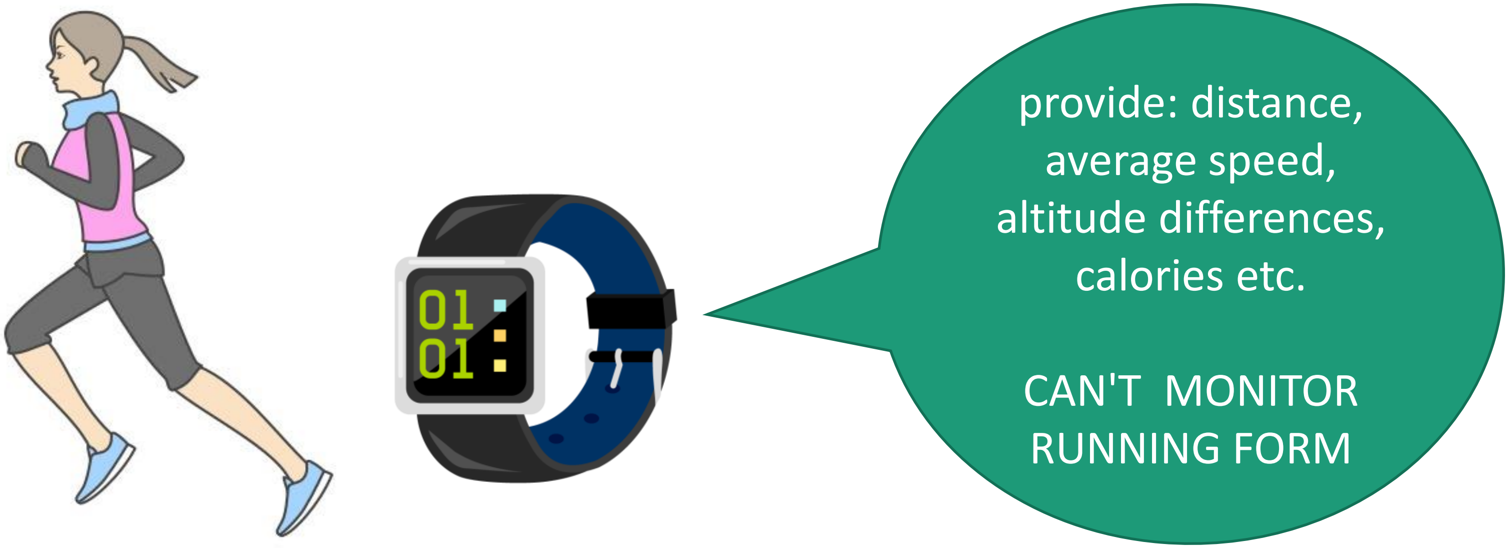
- 1998-2002, Research Associate, Department of Applied Physics, Seikei University, Tokyo Japan.
- 2003-, Associate Professor, Department of Mechanical Engineering, Kochi University of Technology, Kochi Japan.

Research interests:

- human dynamics in healthcare, medical and welfare
- self healthcare engineering
- sensor system for gait analysis
- energy-regenerative welfare orthoses

1. Introduction

One of the sports to promote health is jogging and running. Due to its simplicity, about 10% of the population in Japan practices it [1]. In addition, many wearable devices (such as smart watches) that record running motion are commercially available. Many of these provide data such as distance, average speed, altitude differences, calories, and so on. If the running activity is performed using correct form, a beneficial effect for health can be expected; however, if an incorrect form is used, it may cause damage to the knees and foot soles. However, a simple smart watch cannot easily monitor a person's running form.



1. Introduction

The Ground Reaction Force (GRF) is a way of quantitatively evaluating a form [2]. The magnitude and phase of GRF can indicate the quality of the form. Conventionally, GRF is measured by using an installation type or sole mounting type force plate, which is expensive, causes an uncomfortable form, and cannot be used for measurement over a long distance.

Conventional force plate to measure GRF

Not enough

https://www.tecgihan.co.jp/products/category/forceplate/

1. Introduction

The purpose of this study:

Development a wearable system that can easily monitor GRF during daily running

Obtaining GRF, which can assess running form, as a one of health information could be useful in designing one's own health promotion for effective exercise.

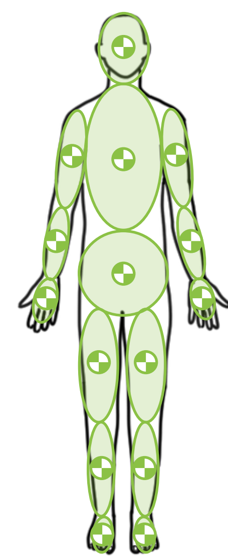
1. Introduction

So far, we have proposed a method to estimate GRF during walking without using Force Plate (FP) [3]. In this estimation system, the whole body is divided into 15 parts. The inertial force of each part is derived from the dynamic acceleration measured by Inertial Measurement Unit (IMU) attached to each part. In the vertical direction, the sum of the inertial force of each part and the gravity balances GRF, so that GRF during walking can be estimated. Similarly, in the anterior-posterior direction, the sum of the inertial forces of the respective parts balances GRF.

Using the force balance relationship

GRF of the vertical direction: $$F_Z = \sum_{i=1}^{15} \underbrace{m_i a_{z_i}}_{\text{Inertial force of each part}} + Mg$$

GRF of the anterior-posterior direction: $$F_Y = \sum_{i=1}^{15} \overbrace{m_i a_{y_i}}^{\text{Inertial force of each part}}$$



[3] A. Isshiki, Y. Inoue, K. Shibata, M. Sonobe, "Estimation of floor reaction force during walking using physical inertial force by wireless motion sensor," HCI Intl. 2017, pp. 249-254, 2017.

1. Introduction

Three major differences between running and walking.

- Running is a faster movement, so the acceleration is large, and the impact force is large.
- When running, there is no two-leg support period.
- There is a period when neither foot is on the ground (referred to as the "aerial period" in this report).

In this report,

(1) we experimentally examine whether the estimation method for walking with IMUs described above can be applied to running. At this time, the GRF is corrected for the aerial period.

(2) we propose to reduce the number of sensors mounting positions from 15 to 5 using the correlation so that the runner can more easily perform the measurements.

2. Estimation of GRF During Running

Body part(s)	Mass ratio (one side)	Parameter notation	
		Mass ratio	Acceleration
Head	0.069	R_{hd}	a_{hd}
Upper trunk	0.302	R_{ut}	a_{ut}
Lower trunk	0.187	R_{lt}	a_{lt}
Upper arm (x2)	0.027	R_{ua}	a_{ua}
Forearm (x2)	0.016	R_{fa}	a_{fa}
Hand (x2)	0.006	R_{hn}	a_{hn}
Thigh (x2)	0.110	R_{th}	a_{th}
Shank (x2)	0.051	R_{sh}	a_{sh}
Foot (x2)	0.011	R_{ft}	a_{ft}

[4] M. Ae, 1992. (in Japanese)

The vertical GRF

$$F_Z = \sum_{i=1}^{15} m_i a_{z_i} + Mg$$

$$= (R_{hd}a_{hdz} + R_{ut}a_{utz} + R_{lt}a_{ltz}$$

$$+R_{ua}a_{uarz} + R_{ua}a_{ualz} + R_{fa}a_{farz} + R_{fa}a_{falz} + R_{hn}a_{hnrz} + R_{hn}a_{hnlz}$$

$$+R_{th}a_{thrz} + R_{th}a_{thlz} + R_{sh}a_{shrz} + R_{sh}a_{shlz} + R_{ft}a_{ftrz} + R_{ft}a_{ftlz}) + Mg$$

The anterior-posterior GRF

$$F_Y = \sum_{i=1}^{15} m_i a_{y_i}$$

$$= R_{hd}a_{hdy} + R_{ut}a_{uty} + R_{lt}a_{lty}$$

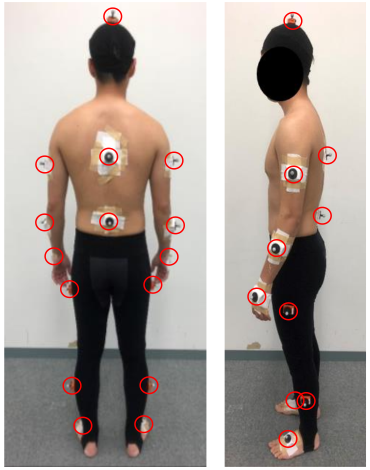
$$+R_{ua}a_{uary} + R_{ua}a_{ualy} + R_{fa}a_{fary} + R_{fa}a_{faly} + R_{hn}a_{hnry} + R_{hn}a_{hnly}$$

$$+R_{th}a_{thry} + R_{th}a_{thly} + R_{sh}a_{shry} + R_{sh}a_{shly} + R_{ft}a_{ftry} + R_{ft}a_{ftly}$$

2. Estimation of GRF During Running

Running experiments

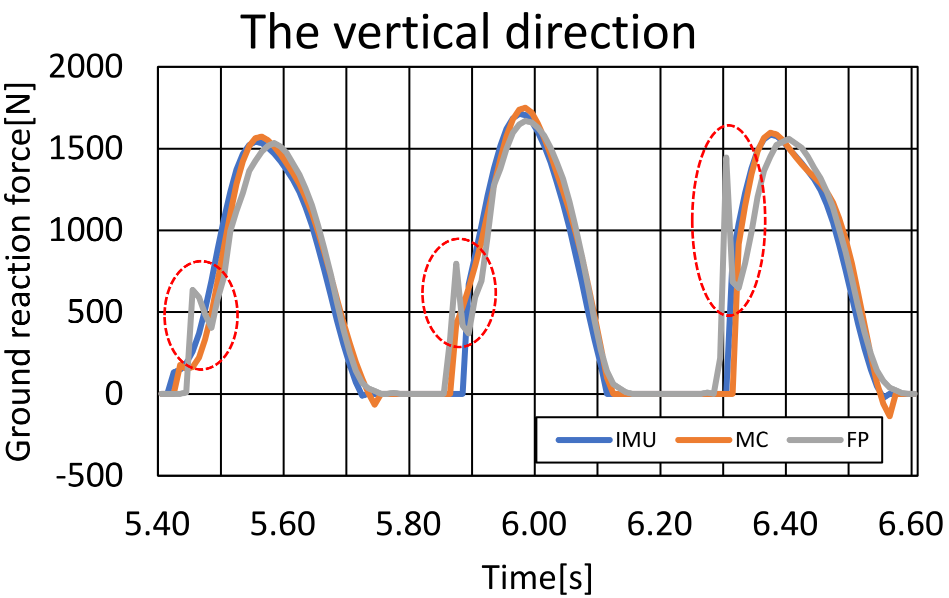
- Three healthy Japanese male volunteers (Age: 21.3 ± 0.7, Height: 1.69 ± 0.03[m], Weight: 68.3 ± 0.2[kg]).
- Three free-running measurements per subject.
- Devices
  - 15 IMUs (MTw2, Xsens)
  - Motion Capture (MC, MAC3D, Motion Analysis)
  - Three FPs (one TF-6090 and two TF-4060, Tec Gihan)
- The sampling frequency is 100[Hz], and the cutoff frequency of the low pass filter for smoothing is 9[Hz].
- The comparison target is the 5th to 7th step on the FPs.
- This experiment is approved by the Kochi University of Technology Ethics Review Committee.

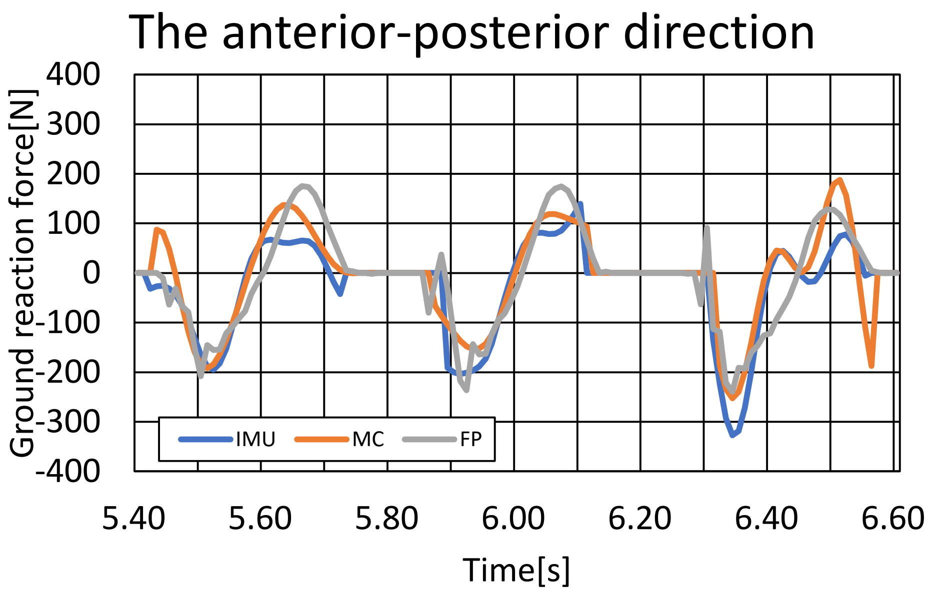


○ MC marker on IMU

2. Estimation of GRF During Running

Running experimental result (with the aerial period correction)





with FP	MAE [N]	Correlation coefficient
for IMU	127.4	0.943
for MC	96.0	0.953

with FP	MAE [N]	Correlation coefficient
for IMU	42.1	0.842
for MC	34.6	0.848

2. Estimation of GRF During Running

For vertical direction

- The estimated waveforms obtained by MC and IMUs matched very well with the FPs as the true value.
- However, the spike wave could not be detected at IMU and MC.

For anterior-posterior direction

- There is a difference in peak magnitude compared to FPs value for both MC and IMUs.
- In addition, phase differences also occurred.
- So, the accuracy was lower than in the vertical direction.

For the proposed estimation method by IMU

- Although we were concerned about a loss of accuracy in the acceleration measurement with the IMU, the two methods by IMU or MC had almost waveforms, and errors introduced by the IMUs were not a problem.

3. Reduction of the Number of Measured Parts

To simplify measurements, reduce the number of IMUs from 15 to 5.

Reduction method:

- When the acceleration values of multiple parts show similar tendency, a representative part is selected.
- The acceleration of the representative part replaces the acceleration of the remaining parts.

3. Reduction of the Number of Measured Parts

1) The five groups with similar tendency for each direction.

(A) Head, Upper trunk, Lower trunk

(B) Upper arm, Forearm, Hand

- right side
- left side

(C) Thigh, Shank, Foot

- right side
- left side

2) An equivalent acceleration is derived for each group.

e.g., the equivalent acceleration of group (A) :

$$a'_{eqAz} = \frac{(R_{hd}a_{hdz} + R_{ut}a_{utz} + R_{lt}a_{ltz})}{(R_{hd} + R_{ut} + R_{lt})}$$

3) Using the measured values, the equivalent acceleration is compared with the acceleration of each part in the group based on the correlation coefficient.

3. Reduction of the Number of Measured Parts

Vertical acceleration in Group (A)

Body part	Head	Upper trunk	Lower trunk
Correlation coefficient	0.978	**0.989**	0.986

Vertical acceleration in Group (B) right side

Body part	Upper arm	Forearm	Hand
Correlation coefficient	0.995	**0.998**	0.964

Vertical acceleration in Group (B) left side

Body part	Upper arm	Forearm	Hand
Correlation coefficient	0.994	**0.998**	0.966

Vertical acceleration in Group (C) right side

Body part	Thigh	Shank	Foot
Correlation coefficient	**0.976**	0.882	-0.112

Vertical acceleration in Group (C) left side

Body part	Thigh	Shank	Foot
Correlation coefficient	**0.969**	0.883	0.014

3. Reduction of the Number of Measured Parts

Anterior-posterior acceleration in Group (A)

Body part	Head	Upper trunk	Lower trunk
Correlation coefficient	-0.213	**0.857**	0.801

Anterior-posterior acceleration in Group (B) right side

Body part	Upper arm	Forearm	Hand
Correlation coefficient	0.993	**0.947**	0.839

Anterior-posterior acceleration in Group (B) left side

Body part	Upper arm	Forearm	Hand
Correlation coefficient	0.946	**0.961**	0.880

Anterior-posterior acceleration in Group (C) right side

Body part	Thigh	Shank	Foot
Correlation coefficient	0.908	**0.963**	0.253

Anterior-posterior acceleration in Group (C) left side

Body part	Thigh	Shank	Foot
Correlation coefficient	0.907	**0.934**	0.432

3. Reduction of the Number of Measured Parts

4) From Tables, in each group, the part with the highest correlation is selected as the representative part.

Estimated vertical GRF
using only the representative part accelerations:

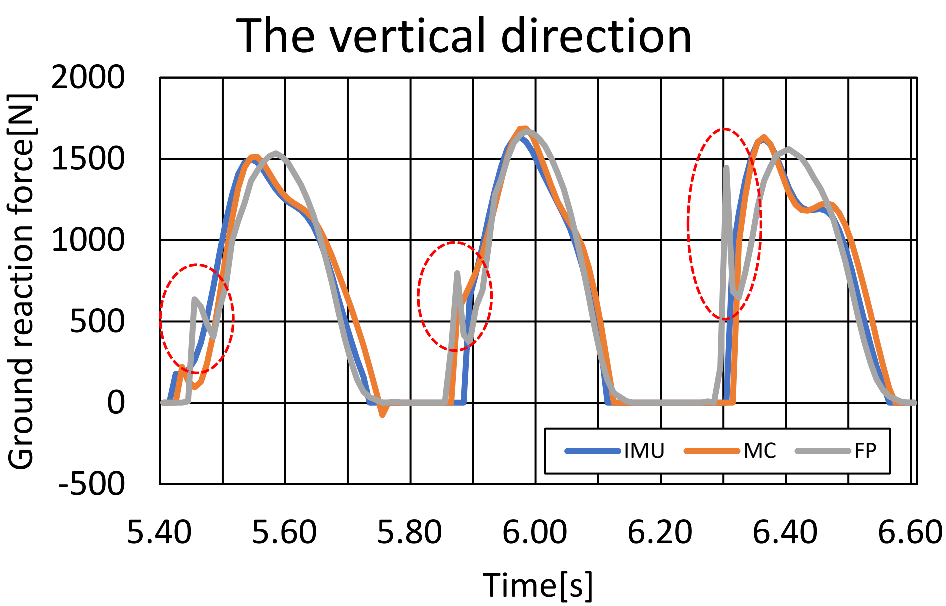
$$F_{r\_z} = \{(R_{hd} + R_{ut} + R_{lt})a_{utz} + \left(R_{ua} + R_{fa} + R_{hn}\right)(a_{farz} + a_{falz}) \\ + \left(R_{th} + R_{sh} + R_{ft}\right)(a_{thrz} + a_{thlz})\}M + Mg$$

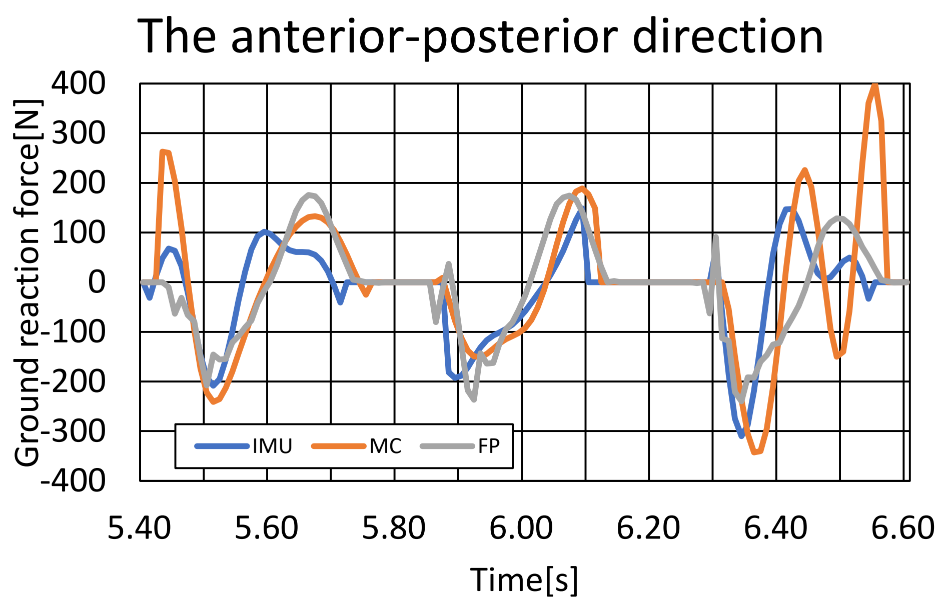
Estimated anterior-posterior GRF
using only the representative part accelerations:

$$F_{r\_Y} = \{(R_{hd} + R_{ut} + R_{lt})a_{uty} + \left(R_{ua} + R_{fa} + R_{hn}\right)(a_{fary} + a_{faly}) \\ + \left(R_{th} + R_{sh} + R_{ft}\right)(a_{shry} + a_{shly})\}M$$

3. Reduction of the Number of Measured Parts

Reduction experimental result (with the aerial period correction)





with FP	MAE [N]	Correlation coefficient
for IMU	142.7	0.928
for MC	147.6	0.925

with FP	MAE [N]	Correlation coefficient
for IMU	55.6	0.693
for MC	55.6	0.765

3. Reduction of the Number of Measured Parts

For vertical direction

- Generally similar tendency could be read for both IMU and MC, and there was no difference in the peak value from the true value.
- Furthermore, it is noteworthy that the estimated GRFs by IMU and by MC agree well, as they did before the reduction.
- Therefore, the accuracy of vertical acceleration measurements using the IMU was good.

For anterior-posterior direction

- Although the general shapes were somewhat similar, both the waveform, peak value, and phase differed from the true value.

3. Reduction of the Number of Measured Parts

Effect of reducing the number of sensors from 15 to 5

For vertical direction

- There is some error in the waveform after the peak value, but the reduction in accuracy is small.

For anterior-posterior direction

- The timing of the increase/decrease is the same, but errors occur, especially in positive magnitude.

4. Conclusion and Future Work

(1) An estimation method used for the walking motion was applied to the running motion to estimate GRFs using wearable IMUs.

- The vertical GRF value estimated from the accelerations measured by the IMUs matched the measured FP value with good accuracy. However, the spike wave immediately after grounding could not be obtained in this report.
- The estimated anterior-posterior GRF value has low accuracy.

(2) We proposed a method of reducing the number of sensors using equivalent acceleration and correlation coefficients.

- In the vertical direction, the proposed reduction method maintained high accuracy.
- In the anterior-posterior GRF, the accuracy was further reduced compared to that before the reduction. In addition, the phase shift became larger.

➔ From the above, we have established a wearable estimation method for vertical GRF during running that reduces the burden on runners.

4. Conclusion and Future Work

In the future,

- Improved the estimation accuracy of the two-directional GRF
  - Selection of appropriate sensor system, e.g., its sampling frequency of 200[Hz] or higher.
  - Selection of the best mounting method to avoid IMU rotational misalignment.
  - The introduction of frequency analysis to capture the characteristics of the waveforms.
- Application of the proposed method to running with higher speeds and long-distance with IMUs.
  - Use of Kalman filter to compensate for drift error, which is generally a problem for long-time measurements in IMU.

Acknowledgments

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