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

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Abstract— **Many people run to maintain or improve their health. If we can monitor our own form during daily running, it is useful in designing our own health promotion for effective exercise. The ground reaction force is a way of quantitatively evaluating a running form. Therefore, to obtain ground reaction force as health information with light burden to runners, this study will develop a wearable estimation method of ground reaction force. So far, we have established a method during walking using 15 inertial measurement units. Therefore, this report applies it and estimates ground reaction forces in two directions while running. Furthermore, we propose to reduce the number of sensors to 5 using correlation between accelerations so that the runner can more easily perform the measurements. The estimated values by each proposed method are compared with the measured values. The results showed that the high accuracy of the vertical ground reaction force was maintained after the reduction, but in the anterior-posterior direction, the high accuracy was not achieved.**

Keywords-health promotion; inertial measurement unit; correlation coefficient; force plate; inertial force.

I. 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.

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 measure a long distance. Therefore, this study develops 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.

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.

There are three major differences between running and walking. First, running is a faster movement, so the acceleration is large and the impact force is large. Second, when running, there is no two-leg support period. Third, there is a period when neither foot is on the ground (referred to as the "aerial period" in this report). Thus, in this report, 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 phase. Furthermore, 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. In addition, the accuracy in estimation is examined. In this estimation, the vertical and the anterior-posterior directions are targeted. Section II describes an estimating method for GRFs and running experiments. Section III proposes a method to reduce the number of sensors and confirms the accuracy from experimental results. Finally, Section IV presents the conclusions.

II. ESTIMATION OF GRFS DURING RUNNING

In this study, the whole body is divided into the 15 parts shown in Table 1, referring to the work by Ae et al. [4]. An inertial force of each part is derived from a mass of each part m_i and each dynamic acceleration a_i, and when these are added, the total inertial force of the whole body is obtained. The sum of the total inertial force and the gravity balances the vertical GRF. If the whole body mass is M, then the vertical GRF F_z can be expressed by (1).

$$F_z = \sum_{i=1}^{15} m_i a_i + Mg \tag{1}$$

Here, m_i can be derived by multiplying M by each body mass ratio [4] R_i in Table 1.

Using vertical dynamic accelerations measured by IMUs,

TABLE I. PHYSICAL INFORMATION [4] AND PARAMETER NOTATION

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}

the vertical GRF F_z can be estimated by the (2). Here, as shown in Table 1, the mass ratio and the acceleration of each part are indicated by subscripts. In addition, for the accelerations of the left and right parts, the subscripts "*l*" and "*r*" are further added to each. Furthermore, the last subscript "*z*" indicates the vertical direction (e.g., the vertical acceleration of the right upper arm is shown as a_{uarz}, and the left one is shown as a_{ualz}).

$$\begin{aligned} F_z = (&R_{hd}a_{hdz} + R_{ut}a_{utz} + R_{lt}a_{ltz} + R_{ua}a_{uarz} + R_{ua}a_{ualz} \\ &+ R_{fa}a_{farz} + R_{fa}a_{falz} + R_{hn}a_{hnrz} + R_{hn}a_{hnlz} + R_{th}a_{thrz} \\ &+ R_{th}a_{thlz} + R_{sh}a_{sharz} + R_{sh}a_{shlz} + R_{ft}a_{ftrz} + R_{ft}a_{ftlz})M + Mg \end{aligned} \tag{2}$$

Furthermore, the anterior-posterior GRF is derived by removing the gravitational term and replacing the vertical acceleration with the anterior-posterior acceleration, in (2).

To examine the accuracy of this proposed method, running experiments are performed. Three healthy Japanese male volunteers (Age: 21.3±0.7, Height: 1.69±0.03[m], Weight: 68.3±0.2[kg]) participated. This experiment is approved by the Kochi University of Technology Ethics Review Committee.

In the experiments, 15 IMUs (MTw2, Xsens), a Motion Capture (MC, MAC3D, Motion Analysis) for obtaining the true value of acceleration, and three FPs (one TF-6090 and two TF-4060, Tec Gihan) for obtaining the true value of GRF are used. Each IMU is attached to the center of mass [4] of the 15 body parts shown in Table 1, and a marker for MC is attached on IMU (Figure 1). Three free-running measurements per subject. 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.

By substituting accelerations measured by IMUs and MC into (2), the GRFs in the vertical and anterior-posterior directions are derived. Furthermore, the GRFs during the aerial period are corrected. The reason for the correction is that the inertia forces calculated from the body part acceleration are not zero because each body part is moving even during the aerial period. In other words, the GRFs derived from the accelerations during the aerial period are not zero. Therefore, the aerial period is estimated based on the vertical dynamic acceleration of the upper trunk, and only the GRFs during the aerial period is corrected to zero.

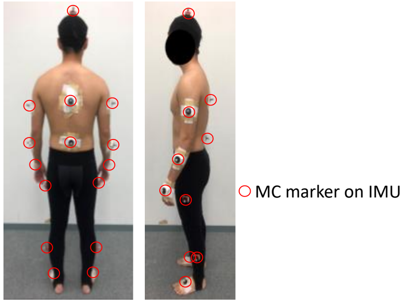

Figure 1. Positions where IMUs and MC markers are attached

The experimental results for one trial of one subject are shown. Other trials have obtained similar results. Figure 2 shows the GRFs estimated from IMUs (blue) or MC (orange) and measured by FPs (gray).

In the vertical GRFs shown in Figure 2(a), the estimated waveforms obtained by MC and IMUs matched very well with the FPs as the true value. The Mean Absolute Error (MAE) with the true value was 127.4 [N] for IMU and 96.0[N] for MC. The correlation coefficient was 0.943 for IMU and 0.953 for MC. However, the spike wave immediately after grounding that appears at FP could not be detected at IMU and MC. On the other hand, the anterior-posterior GRF in Figure 2(b) showed a difference in peak magnitude compared to FPs value for both MC and IMUs. In addition, phase differences also occurred in the estimated values. In the anterior-posterior direction, the MAE with the true value was 42.1[N] for IMU and 34.6[N] for MC. The correlation coefficient was 0.842 for IMU and 0.848 for MC. So, it was found that the accuracy in the anterior-posterior direction was lower than in the vertical direction. Moreover, although we were concerned about a loss of accuracy in the acceleration measurement with the IMU, in this case, the two estimated GRF methods by IMU or MC had almost waveforms, and errors introduced by the IMUs were not a problem.

III. REDUCTION OF THE NUMBER OF MEASURED PARTS

Section II estimated GRFs using the accelerations of all 15 parts of the body. This section proposes to reduce the number of parts to be measured, that is, the number of IMUs, to simplify the measurement.

In the proposed reduction method, when the acceleration values of multiple parts show similar tendency, a representative part is selected, and the acceleration of the representative part replaces the acceleration of the remaining parts. In other words, only accelerations of the representative parts are used to estimate GRFs, thereby reducing the number of measurement points.

A specific method is described. First, the acceleration values measured in the previous experiment are classified into the following three groups with similar tendency.

(A) Head, Upper trunk, Lower trunk
(B) Upper arm, Forearm, Hand
(C) Thigh, Shank, Foot

In fact, the total number of groups is 10, since each group is classified for each direction and for each side. Next, an equivalent acceleration is derived for each group. The equivalent acceleration is obtained by dividing the sum of the inertial forces of the considered parts by the sum of the considered parts masses. For example, the equivalent acceleration of group A in the vertical direction a'_{eqAz} is obtained by

$$a'_{eqAz} = (R_{hd}a_{hdz} + R_{ut}a_{utz} + R_{lt}a_{ltz}) / (R_{hd} + R_{ut} + R_{lt}) \cdot \quad (3)$$

Subsequently, using the measured values of the previous experiment, the equivalent acceleration is compared with the acceleration of each part in the group based on the correlation coefficient. As an example, Table 2 shows the results of group A in the vertical direction. From Table 2, the upper trunk with the highest correlation is selected as the representative part. In this way, representative parts are determined for each of the remaining 9 groups. As results, in this study, the five representative parts in the vertical direction were the upper trunk, right and left forearms, and right and left thighs. On the other hand, the five representative parts in the anterior-posterior direction were the upper trunk, right and left forearms, and right and left shanks.

Hence, for example, the vertical GRF F_{r_z} using only the representative part accelerations can be estimated by

$$\begin{aligned} F_{r\_z} = \{ &(R_{hd} + R_{ut} + R_{lt})a_{utz} + (R_{ua} + R_{fa} + R_{hn})(a_{farz} + a_{falz}) \\ &+ (R_{th} + R_{sh} + R_{ft})(a_{thrz} + a_{thlz})\}M + Mg. \end{aligned} \quad (4)$$

The results of the same trial as in Section II, with this proposed reduction method and correction in the aerial period, are shown. Figure 3 shows GRFs obtained from the five accelerations measured by IMUs or MC, and from FPs.

In the vertical GRF shown in Figure 3(a), no spike wave could be detected as before the reduction (Figure 2(a)). In addition, the waveforms near the peak values of the right foot (5th and 7th steps) were collapsed and the phase also differed. The MAE with the output value of FP as the true value was 142.7[N] for IMU and 147.6[N] for MC. The correlation coefficient was 0.928 for IMU and 0.925 for MC. However, 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. On the other hand, for the anterior-posterior GRF in Figure 3(b), although the general shapes were somewhat similar, both the waveform, peak value, and phase differed from the true value. The MAE with the true value was 55.6[N] for IMU and 55.6[N] for MC. The correlation coefficient was 0.693 for IMU and 0.765 for MC.

Moreover, the effect of reducing the number of sensors from 15 to 5 is discussed. For the vertical direction, from Figures 2(a) and 3(a), there is some error in the waveform after the peak value, but the reduction in accuracy is small. For the anterior-posterior direction, from Figures 2(b) and 3(b), the timing of the increase/decrease is the same, but errors occur, especially in positive magnitude.

TABLE II. THE CORRELATION COEFFICIENT OF VERTICAL ACCELERATIONS IN GROUP A.

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

IV. CONCLUSION AND FUTURE WORK

In this study, an estimation method used for the walking motion was applied to the running motion to estimate GRFs using wearable IMUs. As results, it was confirmed that the vertical GRF value estimated from the accelerations measured by the IMUs matched the measured FP value with good accuracy. However, due to the limitation of the sampling frequency of the IMU used, the spike wave immediately after grounding could not be obtained in this report. Since the IMU with a sampling frequency of 100[Hz] was used in this experiment, this problem could be solved by using a sensor that can measure at a sampling frequency of 200[Hz] or higher. On the other hand, the estimated anterior-posterior GRF value has low accuracy. Since the anterior-posterior acceleration values are small, the rotational misalignment of IMU during running has a significant effect on the estimation accuracy. The results using MC were estimated closer to FP than using IMU. Therefore, we believe that IMU mounting method needs to be improved. Moreover, we proposed a method of reducing the number of sensors using equivalent acceleration and correlation coefficients. In the vertical direction, the estimated GRF after the reduction was slightly less accurate than before the reduction but was almost the same as the measured value. In other words, the proposed reduction method maintained high accuracy. On the other hand, in the anterior-posterior GRF, the accuracy was further reduced compared to that before the reduction. In addition, the phase shift became larger. This result also suggests that one factor in the low accuracy is the misalignment of IMU. Furthermore, another factor was that representative body parts were selected based only on the correlation coefficient of acceleration, and we would like to consider adding the characteristic points of the waveform in the future. One factor was that representative body parts were selected based only on the correlation coefficient of acceleration, and we would like to consider adding the characteristic points of the waveform in the future. From the above, we have established a wearable estimation method for vertical GRF during running that reduces the burden on runners.

In the future, to improve the estimation accuracy of the two-directional GRF, we will consider the selection of appropriate sensor system and mounting methods and the introduction of frequency analysis to capture the characteristics of the waveforms, as described above. In parallel with these, we will explore the applicability of the proposed method to motions with higher running speeds. Furthermore, we will attempt long-distance running with IMUs, although this report we only measured two steps for verification purposes. In this case, we consider using a Kalman filter to compensate for the drift error, which is generally a problem for long-time measurements in IMU.

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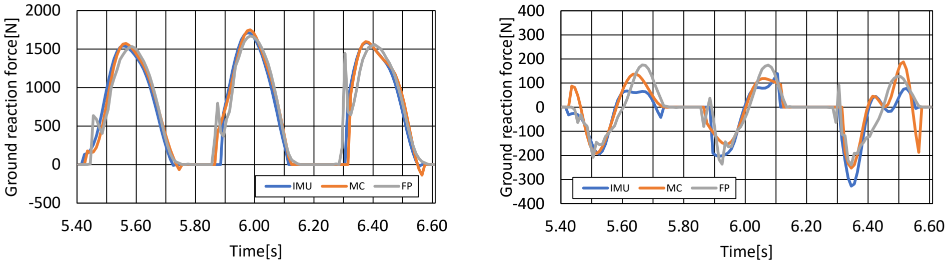
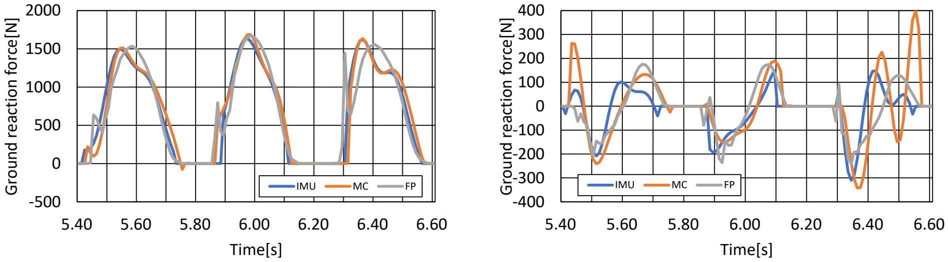


(a)The vertical direction.

(b) The anterior-posterior direction.

Figure 2. The GRFs estimated using 15 IMUs or MC. Here the GRF during the aerial period are corrected.



(a)The vertical direction.

(b) The anterior-posterior direction.

Figure 3. The GRFs estimated using 5 IMUs or MC. Here the GRF during the aerial period are corrected.