Development of a Measurement System Aiming at Detection of Ground Contact in Running and Providing Immediate Feedback Using 3-Axial Acceleration Sensor and Wireless Communication Installed on a Smart Device

Takahiro Tamura*, Ryo Matsuda** and Masaki Suido***

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Abstract In this research, in order to judge whether running movements are good or poor, we have aimed at developing a measurement system using a 3-axial acceleration sensor and a wireless communication function, to verify the possibility of immediate feedback and objective evaluation. Participants, equipped with our new measurement system conducted a 50m run, and we compared the results obtained by the conventional image analysis system and our measurement system. We found that the total number of steps by the image analysis and our measurement systems matched for 2 participants, whereas they were different for 5 participants. To identify a cause for this, we analyzed the acceleration for each of the $x$, $y$, and $z$ axes, from which we considered the resonance caused by the shock of feet hitting the ground, not the body motion, was the cause of the power reduction.

Keywords: quantification of running, immediate feedback, measurement system, 3-axial acceleration sensor, smart device

1. Introduction

In sports, feedback is important to acquire new motor skills for improved performance. In recent years, ICT (information and communication technology) has been introduced with the development of computers and networks, and its use is progressing in feedback scenes. Regarding running, which is a basic exercise movement, not only time, but also pitch, stride, and other factors, are analyzed in a performance evaluation by images obtained using a camera. This image analysis has an advantage that accurate scientific data of the movements can be calculated by frame advancement or slowed reproduction. However, a lot of time is needed for this performance evaluation as most processes (preparing/shooting/analysis/results) are manual, and it is difficult to give immediate feedback after the exercise.

By contrast, as immediate feedback without scientific analysis, Murayama et al.\(^{(1)}\) and Kimura and Iteya\(^{(2)}\) presented a method based on image viewing, and they stated that just checking the images has been effective in correcting and acquiring motor skills. Shimojo et al.\(^{(3)}\) and Chiba and Shirai\(^{(4)}\) explained that since 2007, the JISS (Japan Institute of Sports Science) has developed and operated the SMART system which is an image database system. It can be said that image feedback is generalized. However, it is impossible to obtain an objective evaluation for judging whether the exercise result is good or poor only with viewing information. We expected it would be helpful for improving performance by evaluating results with objective numerical values.

Therefore, in this research, in order to obtain the same accuracy as the conventional image analysis in running, we aimed at verifying whether time, pitch, stride, velocity, and total number of steps can be measured using a 3-axial acceleration sensor. Regarding the accuracy of a step counter using 3-axial acceleration data, Koizumi et al.\(^{(5)}\) reported that there was a significant difference between the real and the measured values at the 5% significance level in a 120 m/min run, and Gindre et al.\(^{(6)}\) reported a similar finding. We note here that an accurate analysis of a step counter has not been established. We conducted measurements at a faster rate and aimed at developing a basic measurement system for easily and accurately analyzing running for all sports in the future.
2. Method

2.1 Experiment Method

In the study, the participants made a 50 m run from the standing start posture on a straight course, and we compared the results of the conventional image analysis system and our measurement system. The experimental protocol is shown in Figure 1. Running movements were obtained as images by a camera carried on a drone [A] (Mavic Pro, manufactured by DJI, 120 fps, 1280×720 p). Also, the motions of the body center of gravity were measured by our measurement system using smart devices [B] (Xperia Z5 Compact, 12×65×8.9 mm, 138 g, manufactured by SOMC), which had a 3-axial acceleration sensor installed. In order to detect accurate waveforms, we asked the participants to sprint about at 70–80% intensity (based on their own feeling) while keeping the best running form as possible.

2.2 Research Participants

The research participants were 8 university students belonging to the athletics department (6 males, 2 females), and their average physical characteristics were as follows: age, 20.38±0.92 years; height, 171.71±6.44 cm; weight, 63.15±9.66 kg. We explained the objectives, experiment details, and possible risks to the participants. The participants fully understood the explanations, and the experiment was carried out under the approval of the Ethics Review Committee of Nakamura Gakuen University.

2.3 Overview of the Measurement System

Figure 2 shows the overview of our measurement system. We utilized the 3-axial acceleration sensor (x, y, z axes) installed in the smart device and the wireless communication function to detect steps. We used smart devices, one for the runner, and another for the experimenter. These devices were connected by a Wi-Fi network, which could be used for communication and synchronization for the 50 m distance [1]. The measurement start/stop was done by manual operation [2], and 3-axial acceleration data on the motion of the body center of gravity of the runner were measured. The sensor of the smart device was fixed on the front of the body in a waist pouch, and the sampling frequency was 125 Hz [3]. We eliminated the influence of gravitational acceleration on the raw x, y and z data so that we did not need to correct the deviation on body movements (back and forth, right and left, up and down). We applied a high-pass filter (HPF) on the measured data to do that. Also, we applied a low-pass filter (LPF) on the windowed data to remove unnecessary vibration then we calculated the absolute values of the vector acceleration sensor (below: the triaxial synthesized values). We set the threshold condition of step deduction as below 5.0 Hz based on the time series data of the triaxial synthesized values, and we eliminated 5.1 Hz or higher values. After that, we calculated the time, pitch, stride, and velocity related to the running movements by algorithmic information processing [4] [5]. Figure 3 shows the step detection standard of the measurement system.
waveform of the triaxial synthesized values could be measured in a time of 200 ms or more, and the threshold value condition was set as the peak value.

2.4 Analysis Method and Data Processing

We set the running period as 50 m (from the start flash to the goal). The taken images were synchronized with the time series data of the triaxial synthesized values from our measurement system, and time could be measured in units of 0.01 s. Then, we specified the ground contact by image analysis, and the consistency was verified by comparing with the step detection of our measurement system. Regarding data such as time, pitch, stride and velocity in the image analysis, we determined the number of ground contacts within the 50 m section as total number of steps and we calculated velocity from the relationship between time and distance. A significant difference statistical analysis was carried out using the t-test with corresponding numerical values from the conventional image analysis and the numerical values calculated from our measurement system. In both cases, the judgment level of significance was set at less than 5%, and SPSS 22.0 was used as the statistical processing software.

3. Results

3.1 Step Determination and Time Series Comparison of Step Detection

As a result of the step determination based on the images of participant A, the right foot contact became an odd number step and there were 25 steps. Figure 4 shows the absolute values of the triaxial synthesized vector of our measurement system: time series data on power detection and image start (0.00 s), 1st step (0.28 s), 5th step (1.43 s), 9th step (2.58 s), 13th step (3.69 s), 17th step (4.80 s), and 21st step (5.93 s). For the time series data of our measurement system, there were 25 peak points on the waveform. Among them, we confirmed that the power detection that appeared at 0.13 s was the motion of the center of gravity at the start posture, when we checked the image. Therefore, we detected the number of step peaks as 24. There was 1 step difference between the measurements of the conventional image analysis and our measurement system; the former detected 25 steps and the latter detected 24 steps. We checked the images of running movements for every step, and compared them with the triaxial synthesized values. As a result, the triaxial synthesized values were clearly lower than the peak value between 4.0 and 4.4 s corresponding to the 15th step (4.24 s). Also, we found that the possibility of not counting a step was very high, since there was about a 3000 (m/s)² difference compared with the waveform values before and after the period between 4.0 and 4.4 s.

Table 1 is a list of running data results of participant A calculated by the measurement system from image analysis and time series data which were shown in Figure 4. Time measurement was accurate as image analysis was done by computers, but our measurement system was not accurate because it used manual remote control, therefore there was a time difference between the image analysis and our measurement system (0.55 s). Total number of steps was 25 steps by image analysis, whereas it was 24 steps by our measurement system. These time and total number of steps were
needed to calculate other data such as pitch, stride, and velocity. However, these values were no match on two analyses.

3.2 Analysis Comparison of Time, Pitch, Stride, Velocity, Steps

Table 2 compares running data of 7 participants when using image analysis and our measurement system for the 50 m run. Since there was some fault on the setting for one participant, we omitted those data. There was a time difference (which is the main factor for running data) between the image analysis and the time measurement made using the remote control (manual operation). The time difference was as follows: minimum value, 0.38 s; maximum value, 0.86 s; and average value, 0.53±0.16 s. The minimum step value was 0 steps, the maximum value was 3 steps, and the average value was 1.1±1.1 steps based on the difference in the steps. Steps obtained by image analysis and the time measurement system matched for 2 participants, whereas they were different for 5 participants (1 step matched for 3 persons, and 2 steps and 3 steps matched for 1 person in each). There was a significant difference in the time, velocity, and steps in the comparison between the image analysis and the running data obtained from the measurement system (p<0.05), but there was no significant difference in pitch and stride.

4. Discussion

4.1 Accuracy of 3-axial Acceleration Sensor Installed on Smart Device

One of the objectives of this research was to verify whether the 3-axial acceleration sensor of the smart device correctly detects the running movements. When we compared the steps for the 50 m run by the conventional image analysis and our measurement system, there were 25 steps by image analysis, but 24 steps by our measurement system. There was a difference of one. The cause of the step mismatch may be some problems in the 15th step around 4.2 s (Figure 4). Figure 5 uses an expanded scale to plot time series data for portions corresponding to the 15th step that we considered to have occurred in this step and the 17th step which was normally detected. Still images captured are also shown. Although each ground contact time was the same at 0.13 s, in the case of the normal 17th step measurement, the peak value of the power at the time of landing exceeded 4000 (m/s^2)^2. However, regarding the 15th step, although there was a power increase/decrease in conjunction while the ground contact, it was clearly different from the 17th step, and the peak value of the power shown by the waveform was low, being around 1000 (m/s^2)^2.

Therefore, we checked the time series data of acceleration measured on the x, y, z axes in order to analyze the changes of acceleration that occurred around the 15th step (Figure 6). As a result, we saw that the
waveform around 4.2 s corresponding to the 15th step on the z axis was disturbed. However, we confirmed the running movements in the image, but did not see a special movement displacement that suddenly changed the rhythm. For this reason, we consider the possibility that the disturbance was caused by other factors than running movements. If the fixation of the waist pouch holding the sensor was inadequate, it might have moved irregularly due to the shock when making the ground contact and the body movements were more than we had expected. Therefore, it is possible to predict that the acceleration caused a resonance with the vertical component and the horizontal component in front and behind, and accidentally set the triaxial synthesized values to a low value.

4.2 Utilization as the Measurement System

The second objective of this research was to develop a new measurement system using smart devices as a means of making effective feedback for improving running performance. Therefore, for the 50 m run, the time of 7 participants calculated from image analysis ranged from 7.70 to 10.11 s. On the other hand, the time for our measurement system ranged from 7.15 to 9.59 s and it was somewhat shorter than for image analysis. This reflects the difference between mechanical detection measurement and manual measurement.

According to books with descriptions on electrical measurements\(^ {7,8} \), manual measurement and time differences, manual timekeeping is faster by approximately +0.20 to 0.24 s. However, the average time difference measured by our measurement system was 0.53±0.16 s. We consider that this error was a problem in our measurement system. In particular, there were two start/stop communications that were prone to error, and we also consider that factors that reduced the time measurement accuracy were in hardware rather than software. Our measurement system connected two smart devices by a wireless communication function to achieve synchronization. There is a possibility that the time lag occurred because the communication between the devices caused a time error that was larger than the usual manual operation.

Regarding the measurement accuracy, there was a significant difference in the number of steps, but the maximum value of the difference was 3.0 steps, the average value was 1.1±1.1 steps, and the detection rate was 95.6±4.2%, so the accuracy was not low. There was no significant difference when converted into pitch and stride. From the above points, we can say that the measurement has a certain accuracy for immediate digitalization of running movements which has been an issue. However, when measuring a sprint such as a 50 m run, the measurement error per step becomes large compared with the measurement in a long distance run such as a marathon, which is also of high importance. Therefore, we consider it necessary to improve the detection accuracy, especially for use as a performance index. To do that, we aim to construct a mechanism for automating start/stop depending on the current manual operation, or to decrease the time lag occurring during synchronization by the wireless communication function of two smart devices. The above points should be addressed as future work.

5. Conclusion

Time series data of a 50 m run were collected using the 3-axial acceleration sensor of a smart device. By conventional image analysis, we found that the step determination of participant A was 25 steps, but in the step detection by our developed measurement system it was 24 steps. Measurement error of one step was judged to have occurred at the 15th step. As a result of analyzing the acceleration of each of the x, y, and z axes, we
considered the resonance caused by the shock of the runner’s feet hitting the ground, not the body movements, was the cause of the power reduction.

The running data of time, pitch, stride, velocity, total number of steps for 7 participants were measured and compared with the numerical values obtained by image analysis. As a result, there was a significant difference in time, velocity, total number of steps, but there was no significant difference in pitch and stride. The main cause of the significant difference was thought to be due to manual operation or measurement error of time by the hardware and these issues will be future research subjects.

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